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TECHNOLOGY RESEARCH, INTEGRATION, AND DEMONSTRATION (TRIAD) PROGRAM

Delivery Order 0013: High Strain Rate Tension Testing of Titanium 6-2-4-2S at Temperature

Susan Hill

University of Dayton Research Institute (UDRI)

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Final Report

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14. ABSTRACT
Constitutive models for advanced titanium alloys are being used to predict structures and life estimates of advanced aircraft. These models require repeatable, reliable data regarding the material behavior at various strain rates and temperatures. The objective of this effort was to perform tensile testing of Ti-6242S under multiple thermal and loading rate conditions to quantitatively capture the constitutive response of the tensile specimens. The data generated can be used to calibrate new constitutive models and to better quantify the accuracy of existing models under relevant loading conditions.

15. SUBJECT TERMS
titanium alloys, tensile testing, high-rate testing

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LIST OF ACRONYMS AND ABBREVIATIONS

A-D	Anderson-Darling test
CL	confidence level
DIC	digital image correlation
fps	frames per second
RA	reduction in area
SH	servo hydraulic
SME	Structures and Materials Evaluation Group
UDRI	University of Dayton Research Institute
UTS	ultimate tensile strength
YS	0.2% offset yield stress

1.0 INTRODUCTION

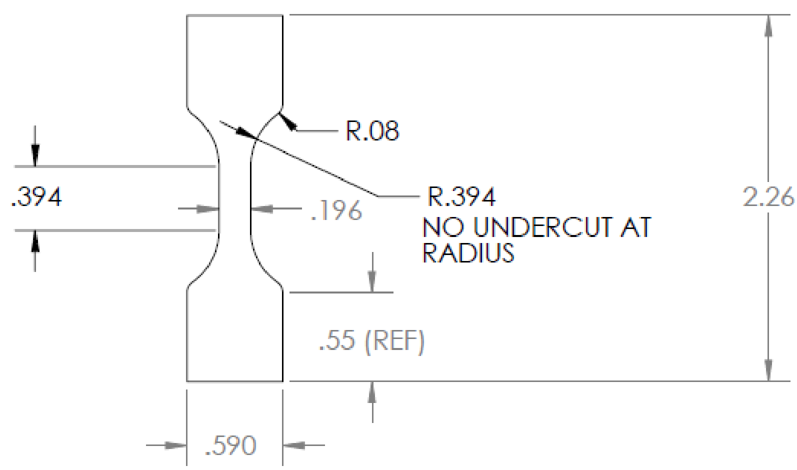
The University of Dayton Research Institute (UDRI) Structures and Materials Evaluation (SME) group was contracted by the United States Air Force Research Laboratory Aerospace Systems Directorate (AFRL/RQHF) to conduct quasi-static and high strain rate tension tests on titanium 6-2-4-2S (Ti 6-2-4-2S) at temperatures ranging from 23° up to 650°C. The tensile coupons were tested at measured post-yield strain rates of 0.01/s up to 100/s. Appendix A provides some background information on the practical considerations of high-rate testing.

2.0 SOURCE MATERIAL AND SPECIMEN LOCATION

AFRL/RQHF provided 1.3 mm-thick sheet Ti 6-2-4-2S. Tensile specimens were machined along the rolling direction per the specimen configuration shown in Figure 1. The specimen identification protocol was as follows:

STLXXX-YYY

where XXX = SME identification number and YYY = Replicate number



Dimensions in inches

Figure 1. Dynamic Rate Tensile Specimen

3.0 TEST MATRIX

Table 1 outlines the final test matrix. Strain was measured using back-to-back strain gages to capture the strain up through yield. Post-yield strain at 23°C and 100°C was determined using a digital image correlation system (DIC). The un-instrumented specimen was used for the machine setup. All tests were performed on servo-hydraulic (SH) test stations. The test matrix also includes the additional runs using flame-sprayed gages.

Table 1. Tensile Test Matrix for Ti 6-2-4-2S

	Temperature		Measured Engineering Post-Yield Strain Rate 1/s			
	°F	°C	0.1	1	10	100-150
Back-to-back strain gages	74	23	5	5	5	5
DIC			5	5	5	5
Un-instrumented			1	1	1	1
Back-to-back strain gages	212	100	5	5	5	5
DIC			5	5	5	5
Un-instrumented			1	1	1	1
Back-to-back strain gages	392	200			5	
Un-instrumented					1	
Back-to-back strain gages	601	316			5	
Un-instrumented			5	5	1	
Back-to-back strain gages	800	427			1	
Un-instrumented			5	5	5	
Back-to-back strain gages	1000	538			1	
Un-instrumented					1	
Back-to-back strain gages	1122	600			1	
Un-instrumented					1	
Back-to-back strain gages	1202	650			5	
Un-instrumented					1	
Total per rate			**32**	**32**	**50**	**22**
Grand Total			**136**			

4.0 TEST PROCEDURES

The test procedures followed the guidelines of SAE J2749[1] "*High Strain Rate Tensile Testing of Polymers*". Specifics are described below. All strain rates refer to measured post-yield engineering strain rates, unless otherwise indicated.

4.1 Surface Preparation

The specimen surface was prepared following the procedures provided by AFRL/RQHF. All specimens underwent the multiple cleaning cycles, as outlined in Appendix B.

4.2 SH Equipment

Tests were performed at room-temperature ambient conditions on MTS SH stations equipped with a 4.4 or 48.9 kN actuator at post-yield strain rates from 0.01/s through 150/s. The specimen was loaded along the shoulder radius, as noted in Figure 2. The room temperature high-speed DIC camera setup is shown in Figure 3.

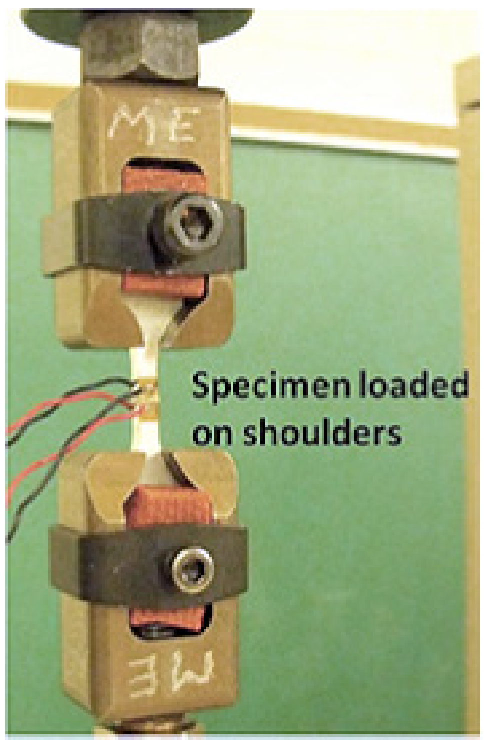


Figure 2. Gaged Specimen in Grip

[1] SAE J2749, "Surface Vehicle Recommended Practice – High Strain Rate Tensile Testing of Polymers," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096, www.sae.org.

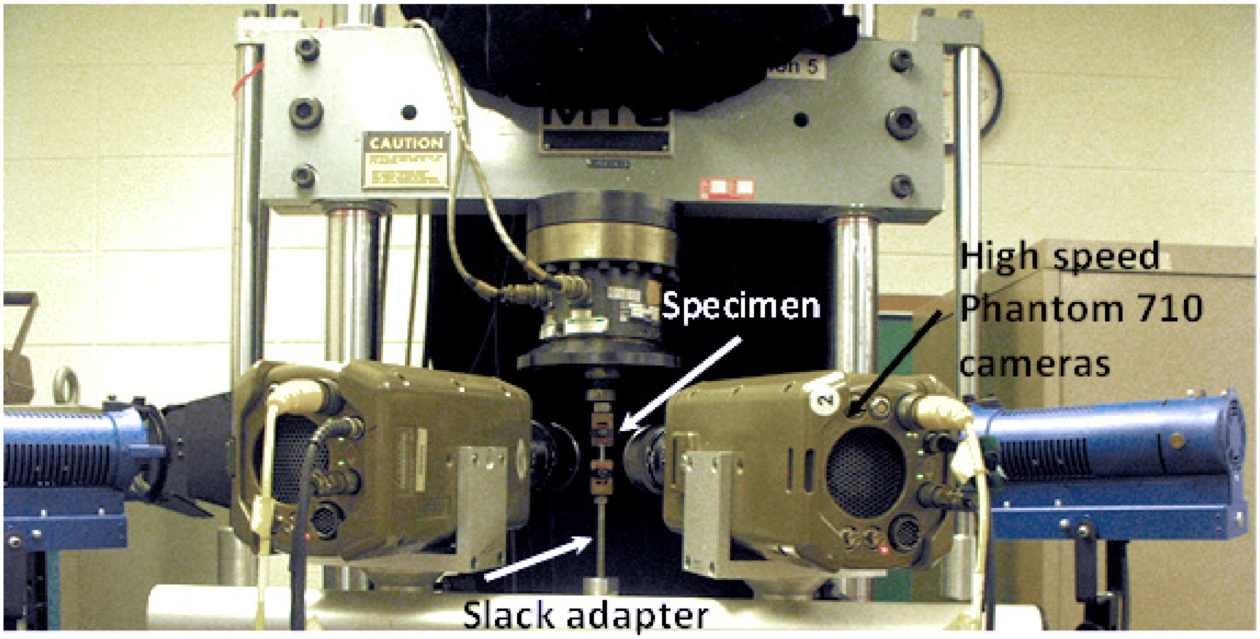


Figure 3. Room-Temperature High-Speed DIC Tensile Setup

A slack adapter was used at all rates. The slack adapter consisted of a cup/cone rod assembly that allowed the actuator to attain a constant test speed before engaging with the fixture and applying load to the test specimen.

Actuator displacement was measured using a linear voltage displacement transducer. The full-scale stroke was 127 mm or 254 mm, depending on the actuator. Data were captured with National Instruments cards (USB 145B938 and PCI 6110E high-speed data acquisition). The various load measurement devices were calibrated up to 11.1 (2000 lb_f) or 22.2 kN (5000 lb_f) full scale. A load cell was used at 0.01/s through 10/s and a piezoelectric washer was used at 100-150/s. An equipment list is given in Appendix C.

4.3 Elevated Temperature Chambers

A chamber with a non-glare-coated window was built for use with the DIC at 100°C. The window allowed for imaging of the specimen during test. The setup is shown in Figures 4 and 5.

A clamshell Applied Test Systems furnace (Series 32) was used at temperatures from 200°C to 650°C. The central zone was approximately 25mm long. The setup is shown in Figures 6 and 7. Boron nitride spray was used on the interior surfaces of the grips to minimize heat transfer into the grip assembly. External cooling was also applied to the conductive fin to increase conductive cooling and avoid overheating the load washer (Figure 6). The maximum useable temperature of the load washer is 177°C.

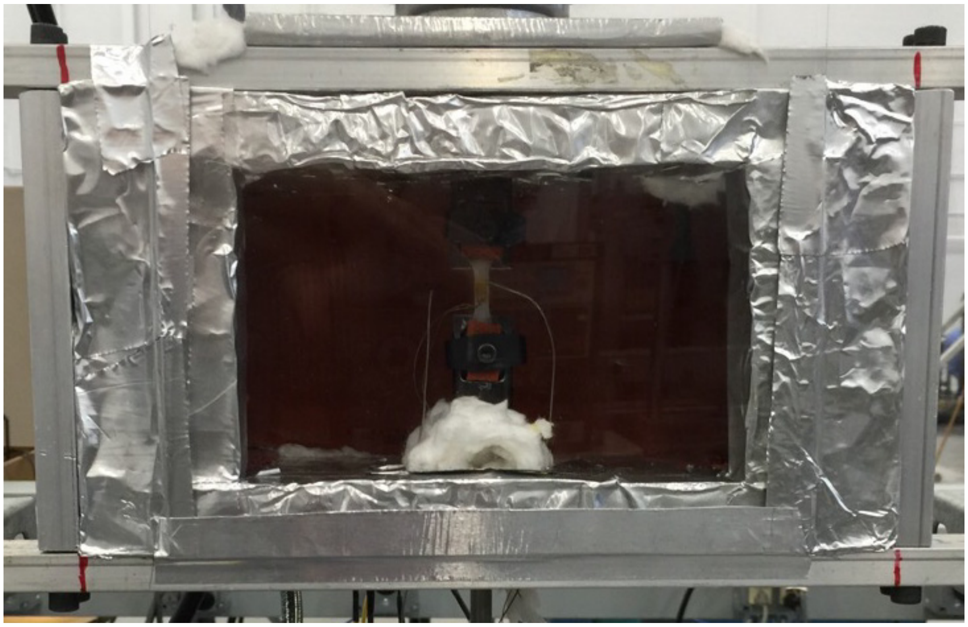


Figure 4. Chamber at 100°C

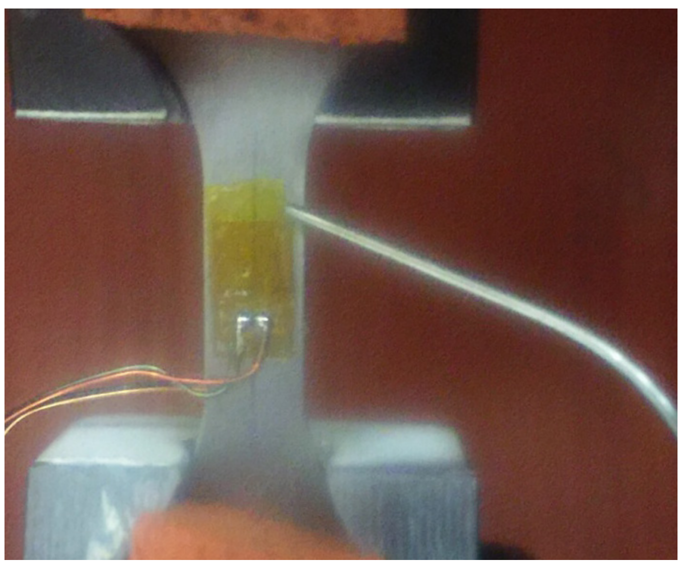


Figure 5. Close-up of Gaged Specimen in Chamber with Thermocouple

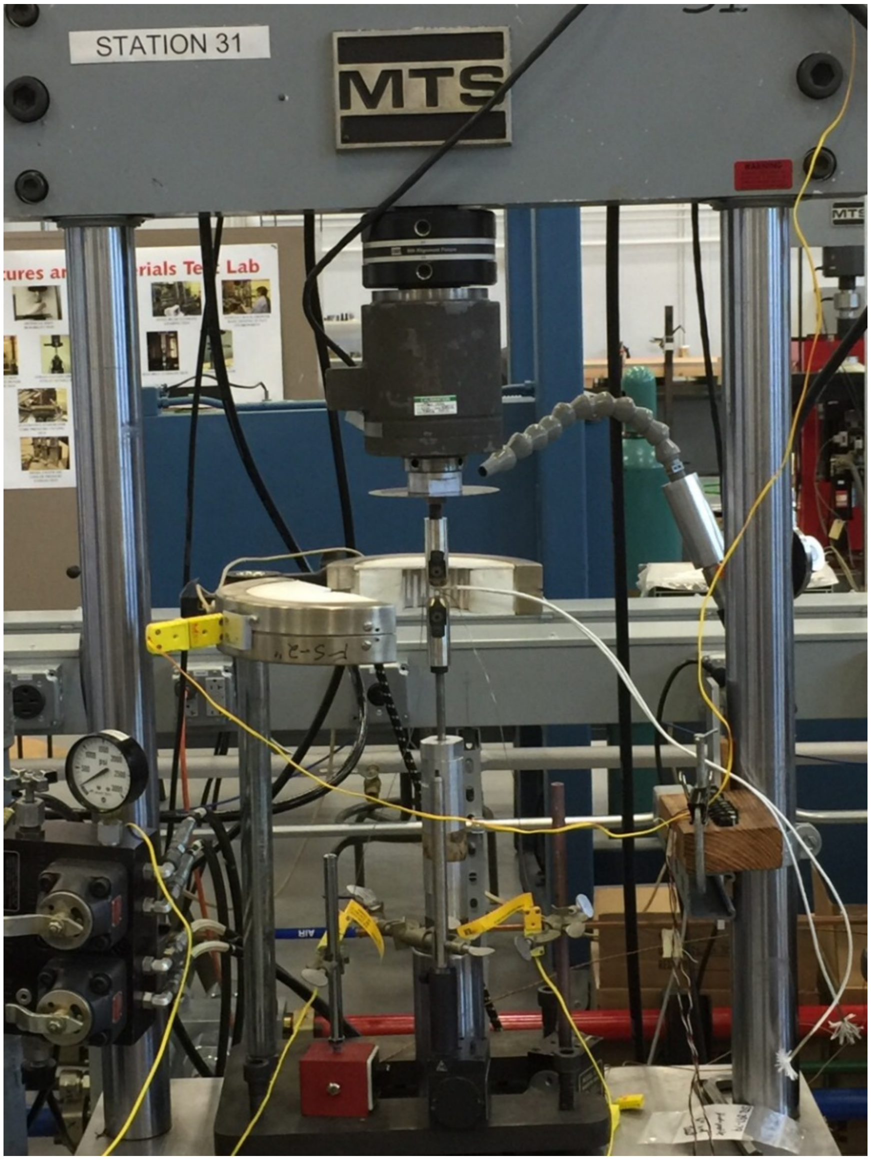


Figure 6. Overall Applied Test Systems Clamshell Furnace Setup

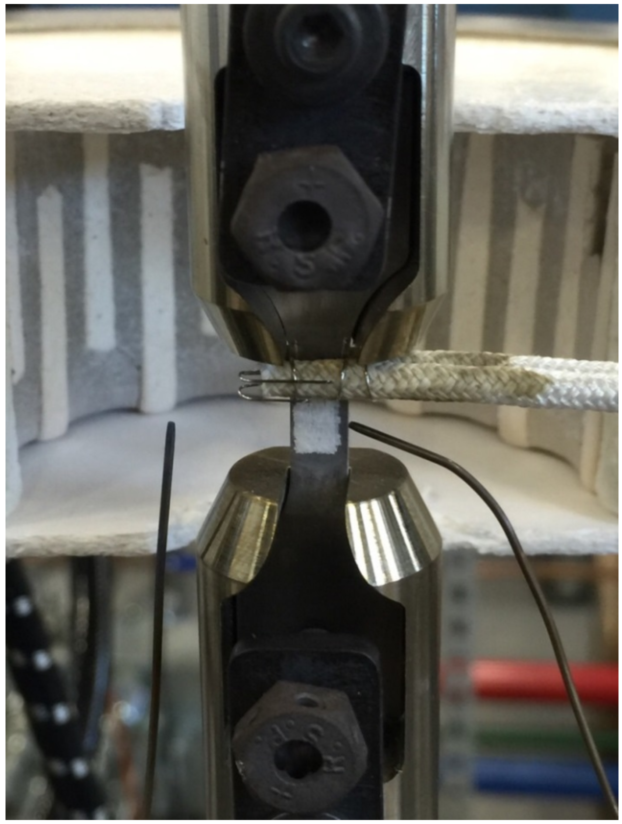


Figure 7. Close-up of Gaged Specimen in Chamber with Thermocouple

4.4 Strain Measurement

4.4.1 *Strain Gages*

Strain gages were located on both faces at the center of the straight gage section. Each gage was wired as a quarter bridge. Data were collected separately for each gage and averaged to compensate for potential bending. The specimen surface was lightly sanded to improve adhesive adherence.

The room-temperature strain gages were Vishay Micro-Measurements (MM) EP[2] 08-031-DE120 and bonded with Vishay Micro-Measurements M-Bond AE-10 adhesive. The full-scale setting was 5% strain.

Strain gages used at 200° and 319°C were Vishay MM WK-06-062AP-350 gages bonded with VishayAS-600 adhesive. The full-scale setting was 2 or 5% strain.

Strain gages at 427°C and above were applied using a flame spray technique at AFRL/RQ. The gages were Hitec Products HFP-12-125-SPW. The full scale for two of the runs was 5% strain

[2] EP gages use a constantan foil with a high-elongation polyimide backing. The EP is specialty annealed to provide high elongation. The WK gages are fully encapsulated and have high-endurance lead wires. WK gages can be used up to 290°C.

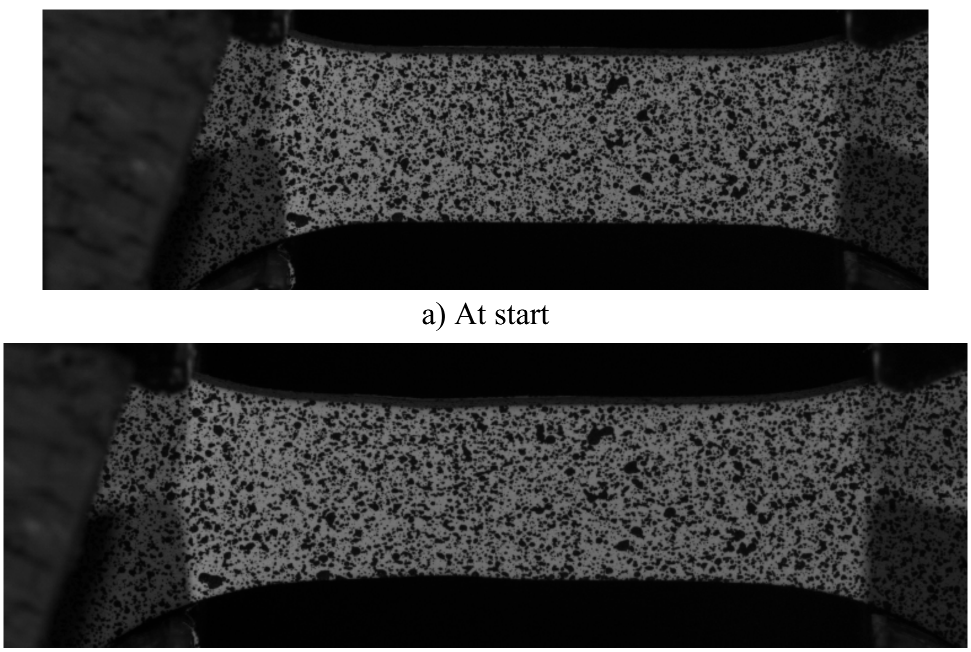
and the balance had a full scale of 2% strain. Technical issues were identified regarding the mechanical bond between the ceramic adhesive and the titanium, as described in Section 6.1.

4.4.2 *DIC with ISTRA Software*

Full-field 3D deformation was measured using two Phantom V710 high-speed cameras (S/N 9327 and 9328) with a maximum resolution of 1,240 by 800 pixels at 500 fps. The camera system used Dantec Dynamic ISTRA DIC software, Version 4.4.0.

The image resolution varied with the filming rate. The framing rates were 2,000 fps (frames per second) at the 0.01/s and 0.1/s test rates, 50 kfps at 10/s, and 100 kfps at 100/s. The corresponding resolutions were 480 × 144 pixels and 512 × 120 pixels for the captured images. The resolution across the specimen image was less than the overall image.

The ISTRA software tracked the motion of a random pattern on the specimen throughout the test. A typical pattern is shown in Figure 8 at the beginning and just before final failure. Three-dimensional analysis of the pattern movement was used to calculate the net displacements and strains of the features of the pattern. The painted speckle pattern was applied using a spray can.



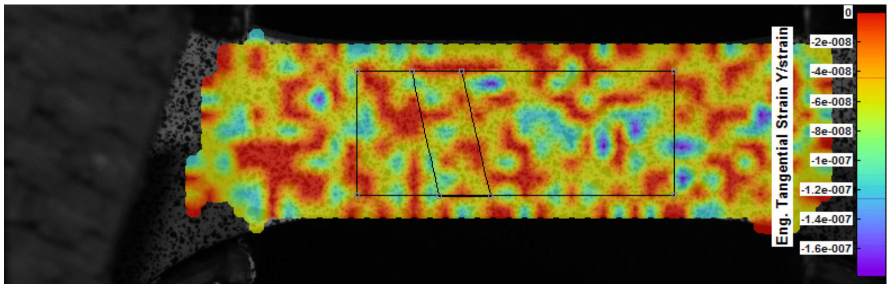
a) At start

b) Before failure

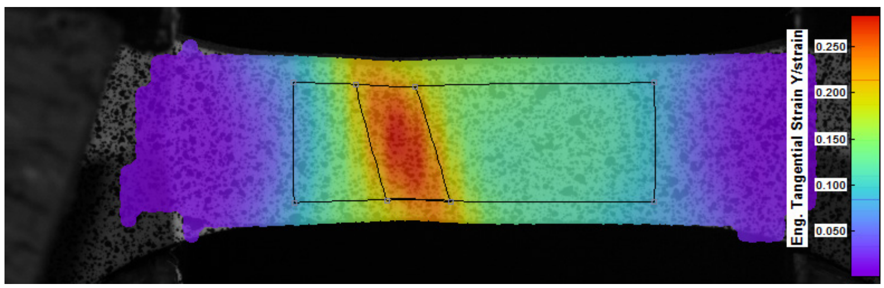
Figure 8. Example of DIC Paint Pattern at Various Stages

The colored region, shown in Figure 9, was the portion analyzed by the ISTRA software. A central polygon was used for all specimens to track a global strain throughout the test. The average length of the global polygon, or its gage length, was approximately 7.5 mm; the average width of the polygon was ~1.8 mm. The polygon gage length was approximately equivalent to an extensometer gage length.

The strain over the region of failure was measured with another polygon (i.e., a local polygon). The localized necking region is marked by the red color in Figure 9b. The starting average size for the local polygon was 1.0 mm long by 2.0 mm wide. The polygon sizes for each specimen are in Appendix D and are included in the data file for the individual specimen.



a) Start of test



b) Before failure

Figure 9. Example of Polygons Used for DIC Strain Measurement

The ISTRA software can only track the pattern if the pattern integrity is maintained. The paint can flake off as the specimen elongates, especially if necking occurs before failure. In these cases, an open area is present in the measured region. The measured DIC strain is influenced by the size and number of the open regions. The portion of the curve in the circled section in Figure 10 shows the change in the as-measured DIC strain data corresponding to a loss in the pattern integrity. These strain data are not representative and the data are truncated.

Strain to fracture was extrapolated if strain data had to be truncated. The extrapolated data was based on the measured strain rate close to the end of the valid region of strain. The extrapolated portion of the strain is indicated in Figure 10, along with the as-measured DIC strain. The resultant failure strain data are conservative since the data extrapolation assumes a constant rate to failure and the strain rate is actually increasing before failure. The point after which strain data are extrapolated is included in the individual specimen file.

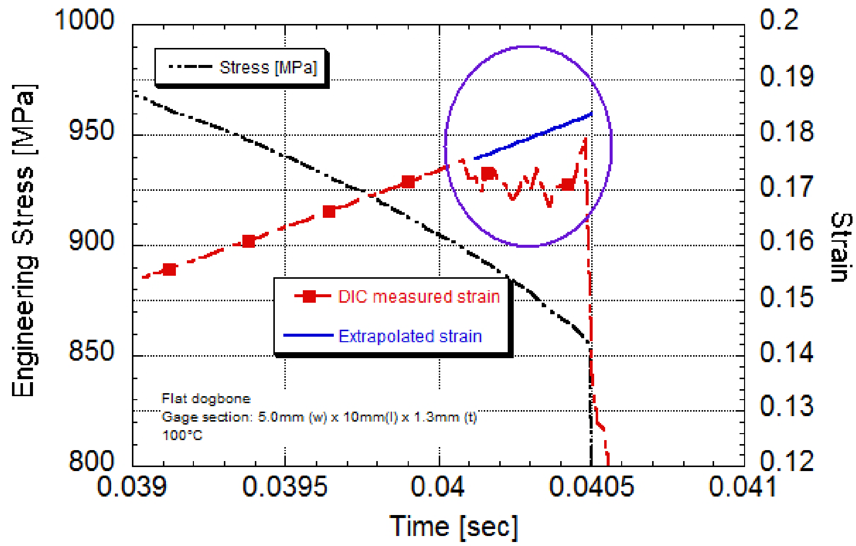


Figure 10. As-Measured and Extrapolated DIC Strain Before Fracture

5.0 DATA ANALYSIS

5.1 Curve Shifting

The DIC system images one face of the specimen and there is no compensation for bending. Since the high-rate fixturing is not a stiff system, as is usually present for quasi-static test stations, there is always a potential for slight bending upon the application of the load.

The strain-gaged specimen curves were used as reference curves since these data were compensated for bending. The DIC curves were shifted along the strain axis, as needed, so that the initial portion of the stress-strain curve through yield coincided with the strain-gaged-based curves. Only the engineering ε_y and true ε_y data were shifted. The ε_x and ε_{xy} data were not shifted.

5.2 Measured Properties

5.2.1 *Modulus*

The measured elastic modulus was determined from the strain-gaged specimens and taken from the slope of the linear best-fit equation to the stress-strain curve between 0 and 600 MPa.

The moduli are for informational purposes only and may not represent the bulk material properties. The test procedures did not meet all of the requirements for modulus measurements per ASTM E 111[3], such as: a longer specimen (and, hence, a larger volume), a Class B-2 or better extensometer, precise alignment, and a slow test speed in order to avoid adiabatic heating.

5.2.2 *Engineering and True Stress*

The average specimen dimensions were used to calculate engineering stress. The 0.2% offset yield strength (YS) for the strain-gaged specimens was found using the measured modulus of the individual specimen. The YS for the DIC-measured specimens were found using the average modulus of the gaged specimens at the same rate. The offset yield strain was the strain at the point of YS.

The gaged specimen true stress and strain data were calculated using Equations 1 and 2:

$$\sigma_t = \sigma_{egr}(1 + \varepsilon_{egr}) \qquad (1)$$

$$\varepsilon_t = \ln(1 + \varepsilon_{egr}) \qquad (2)$$

The DIC true stress was based on the global ε_y strain data. The summary data sets contain the true stress data up to the ultimate tensile strength (UTS).

[3] ASTM E 111, "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus", ASTM International, 100 Bar Harbor Drive, West Conshohocken, PA.

In general, the failure stress was taken at the point of a sudden drop in stress. Failure was identified by comparison of the stress-strain curves, the stress-time curves, the transition towards fracture, and engineering judgment.

5.2.3 *Strain Rate*

A nominal strain rate was calculated for all specimens and listed in the summary table. The nominal strain rate was defined as:

$$\dot{\varepsilon}_{nom} = \dot{\delta} / l_s \qquad (3)$$

where $\dot{\delta}$ is the actuator displacement rate and l_s is the straight gage length (10 mm).

The measured strain rate was calculated over a region of strain that was after yield, but before UTS. This was usually between 2% and 6% strain. The strain-time curve was relatively linear over this range. The measured rate was lower than the nominal rate by a factor of 0.84 to 0.95.

5.2.4 *Elongation and Reduction in Area (RA)*

Elongation and RA were measured on a limited number of specimens. The final length measurements were taken by measuring the distance from the failure edge to the original mark using a travelling microscope. The RA was determined using the following equation:

$$\%\ RA = (A_o - A_f)/A_o \qquad (4)$$

where A_o is the original area and A_f is the average of the failure areas of the two broken halves. The final dimensions were measured using a travelling microscope.

5.3 DIC Strain

The DIC-calculated strain data were taken across the surface of the polygon. Similar polygon sizes were used in order to minimize the effect of variations due to the data analyses. The data were smoothed in 5 by 5-pixel steps using the embedded ISTRA linear regression software.

5.4 Statistical Analysis

The data were analyzed using the k-factor Anderson-Darling (A-D) test (described in MMPD[4], Section 9.5.3, combinability of data), the Student's t-test assuming unequal variances, and the F-test using a 95% confidence level (CL). Comments regarding the significance of the results are based on the results from these analyses.

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[4] Metallic Materials Properties Development and Standardization, Federal Aviation Administration, 2011.

6.0 RESULTS AND DISCUSSION

The mechanical properties of Ti 6-2-4-2S were determined at measured post-yield strain rates of 0.01/s to 150/s. The program CD contains electronic copies of the individual specimen data files, specimen measurements, test data, summary graphs in JPEG and KalediaGraph® format, test setup photographs, and other relevant documents. The engineering and true ε_y strain data reflect any shift needed to zero the response. The ε_x and ε_{xy} data were not shifted.

Analyses of the differences in the measured properties with rate were based on the k-factor A-D test, the two-sided Student's t-test assuming unequal variances, and the F-test using a 95% CL. Comments regarding the significance of the results are based on the results from these analyses.

6.1 Flame Spray Gages

The response of the flame-sprayed gaged specimens was not representative of the material response. Figure 11 shows the difference in the measured initial stress-strain response of flame-sprayed specimens as compared to that measured using the EP or WK gages. In addition to the difference in stiffness, the pre-yield region was nonlinear, as seen in Figure 12. Several tests were run at temperatures from 427°C through 650°C with a similar response. No identifiable cause was found due to the test procedures that would account for the large difference in the measured stiffness of the flame-sprayed specimen.

An inadequate mechanical bond between the flame-sprayed ceramic adhesive and the substrate was suspected. One specimen was manually cycled between 0 and 480 MPa several times and then tested. The measured response through 480 MPa had a lower modulus, perhaps due to the cracks in the adhesive from the cycling. However, once the stress exceeded the peak cyclic stress, the shape of the curve reverted back to the previous runs (Figure 11).

The test matrix was revised to eliminate the elevated-temperature gaged tests in order to focus on un-instrumented runs at 316°C and 427°C.

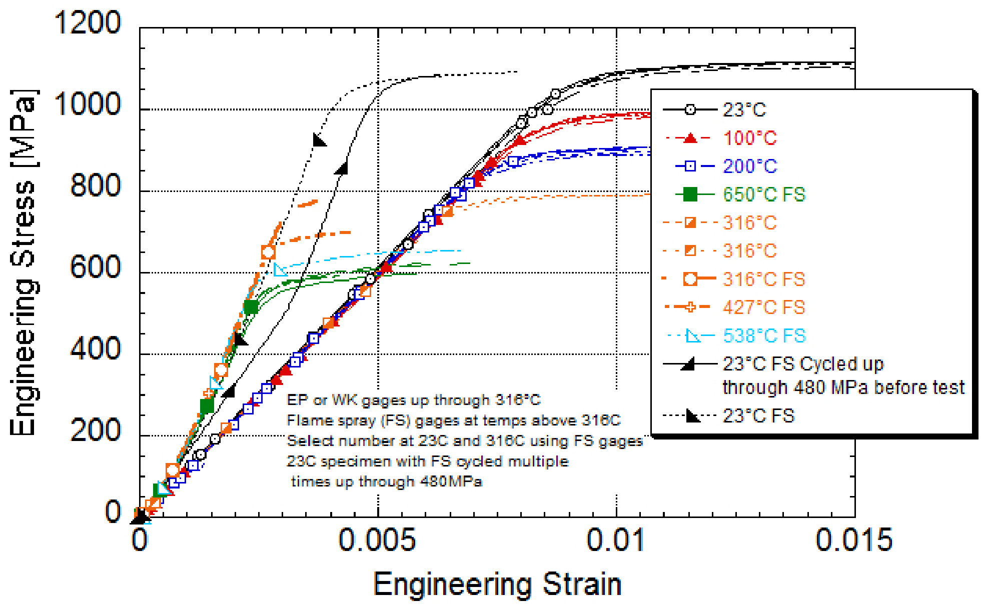


Figure 11. Pre-yield Response at 12/s up Through 650°C Using EP, WK, and Flame-Sprayed Gages

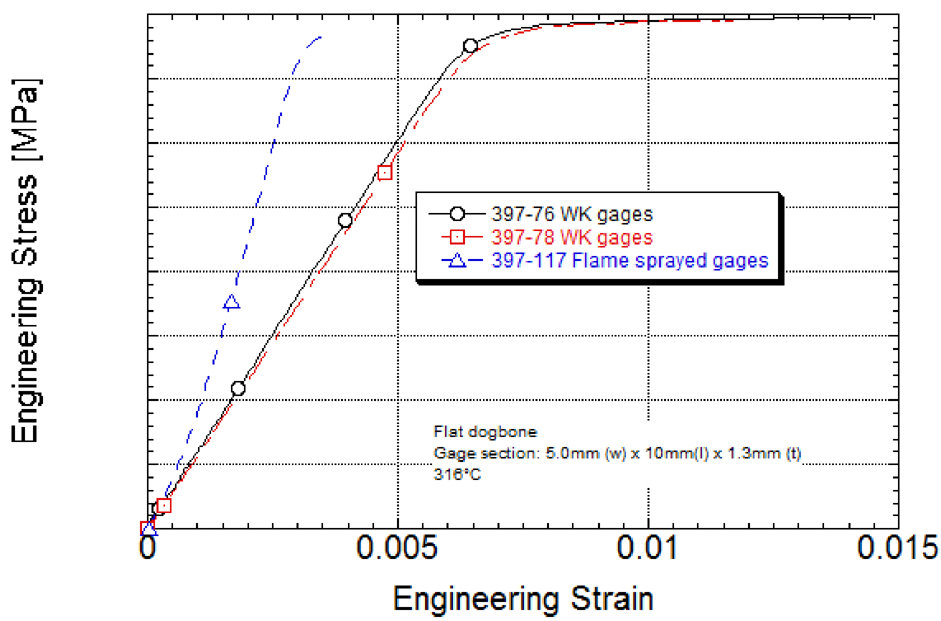


Figure 12. Nonlinear Pre-yield Response at 12/s and 316°C

6.2 Rate Effects

Figures 13 through 18 show the effects of rate and temperature on the measured mechanical properties. Best-fit curves are included where appropriate. The measured mechanical properties are summarized in Tables 2 to 4. Summary stress-strain curves and detailed tables for each temperature and rate are included in Appendices E through J.

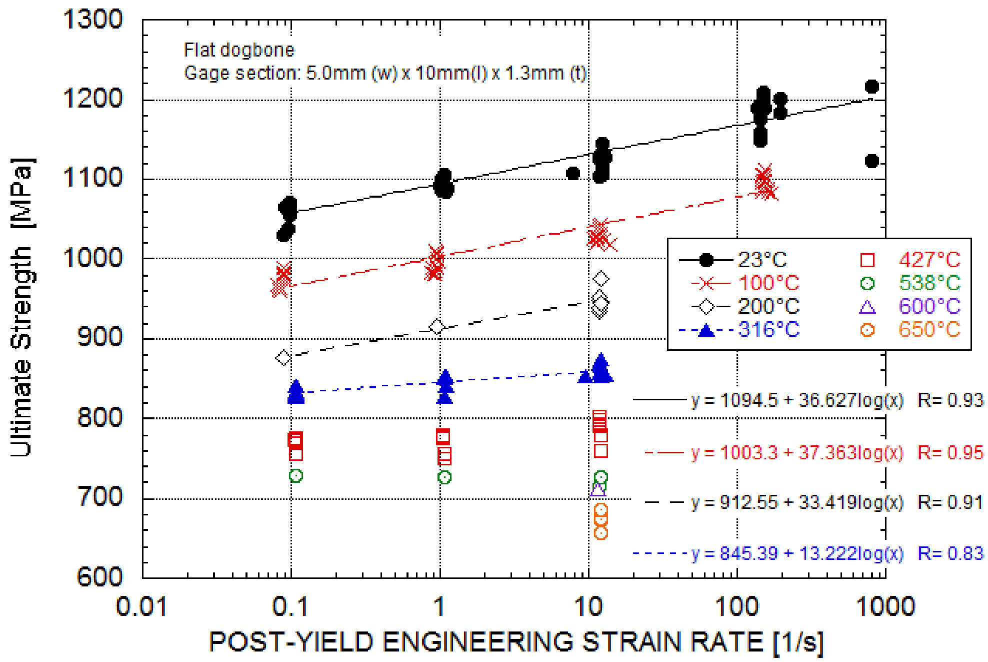


Figure 13. Effect of Increasing Strain Rate on the UTS of Ti 6-2-4-2S Across All Temperatures and Rates

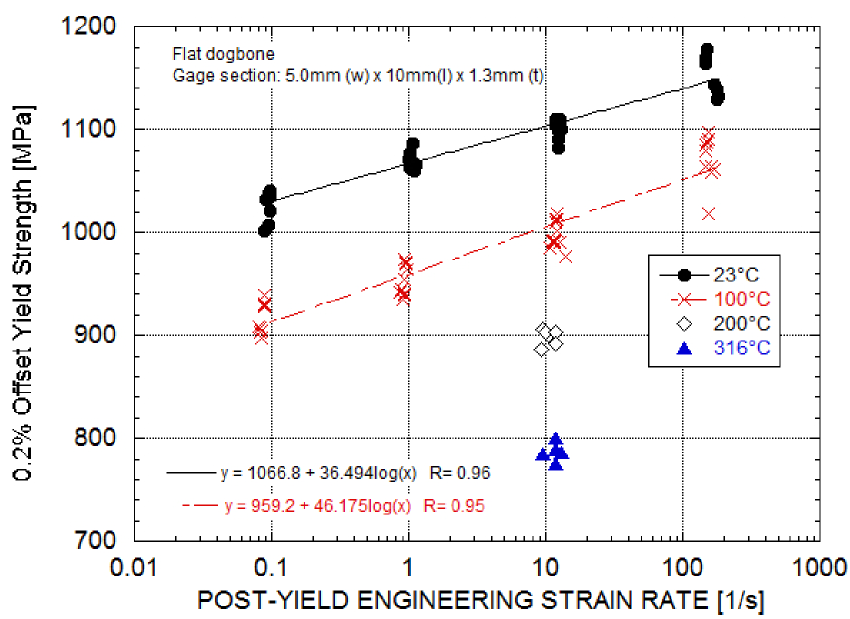


Figure 14. Effect of Increasing Strain Rate on the YS of Ti 6-2-4-2S Across All Temperatures and Rates

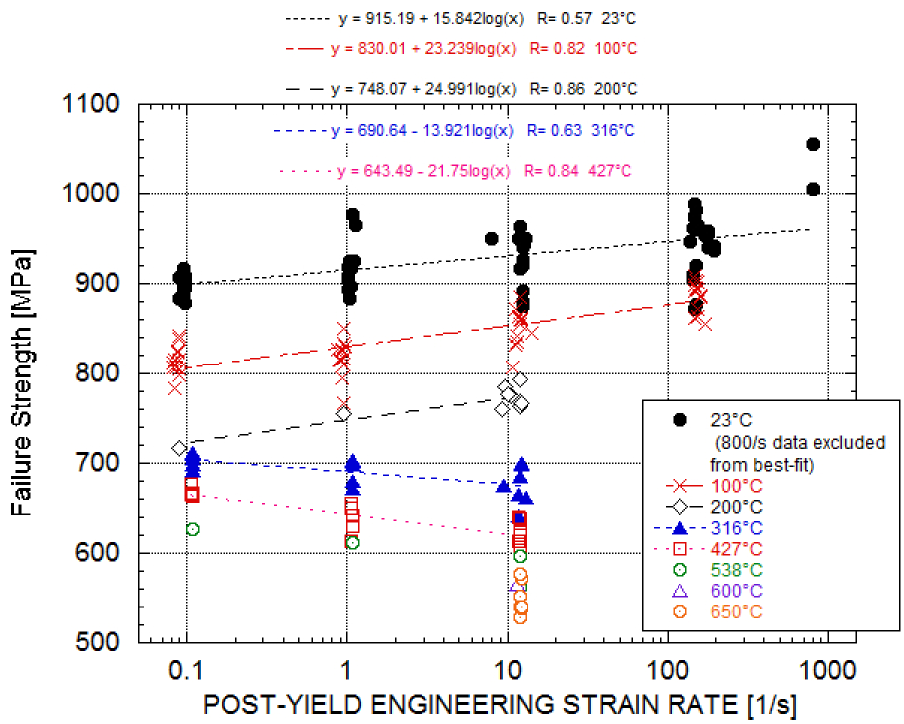


Figure 15. Effect of Increasing Strain Rate on the Failure Strength of Ti 6-2-4-2S Across All Temperatures and Rates

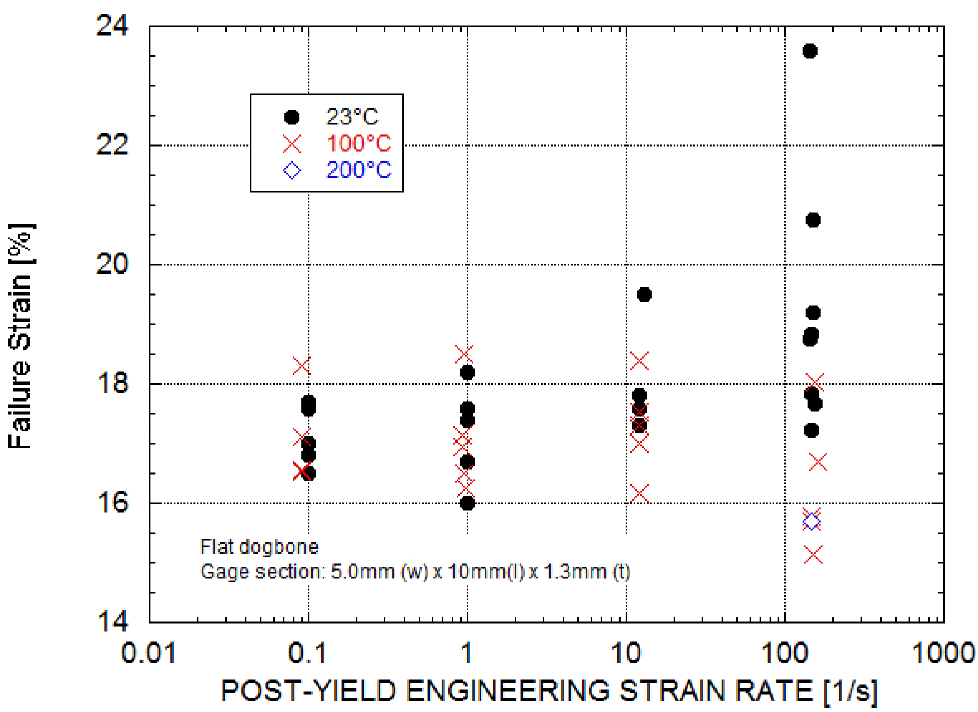


Figure 16. Effect of Increasing Strain Rate on the Failure Strain of Ti 6-2-4-2S Across All Temperatures and Rates

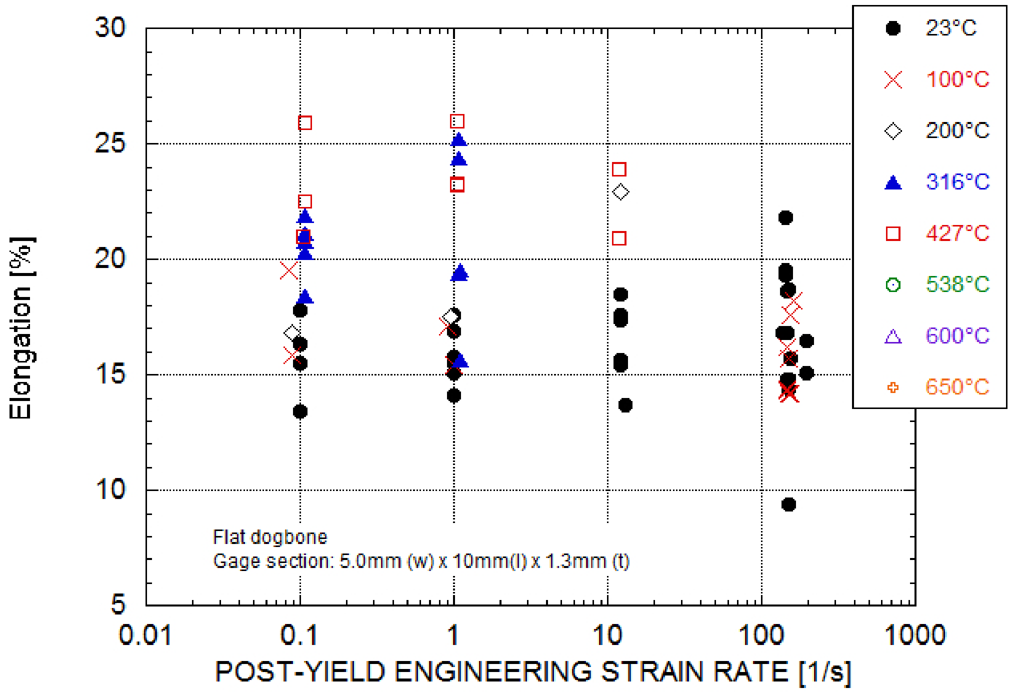


Figure 17. Effect of Increasing Strain Rate on the Elongation of Ti 6-2-4-2S Across All Temperatures and Rates

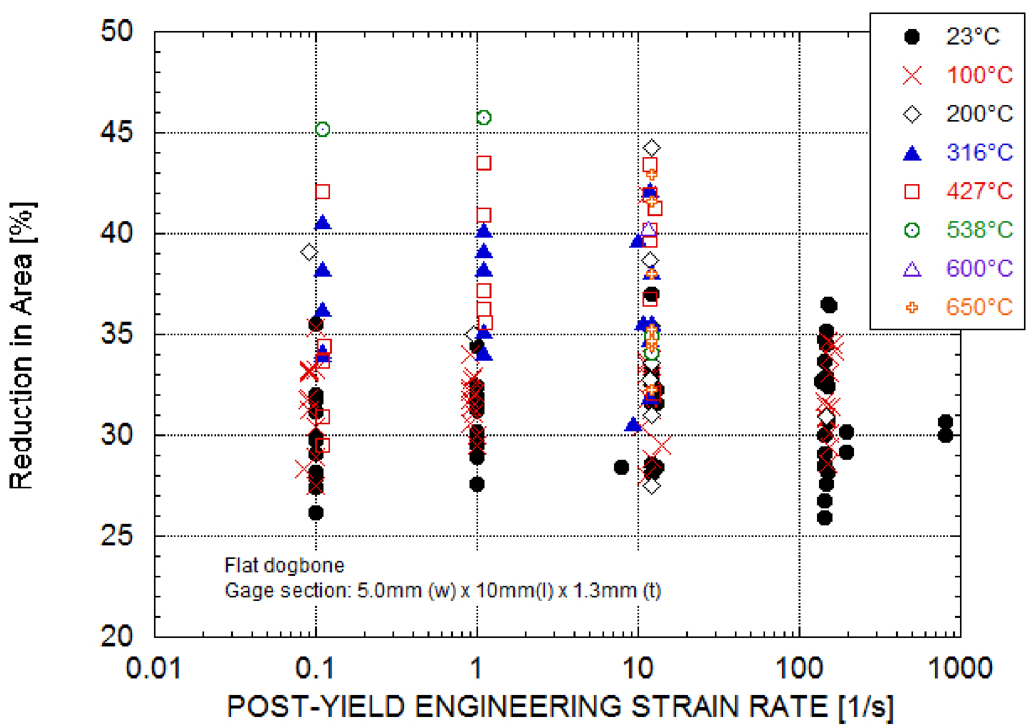


Figure 18. Effect of Increasing Strain Rate on the Reduction in Area of Ti 6-2-4-2S Across All Temperatures and Rates

Table 2. Summary of Ti 6-2-4-2S Mechanical Properties – 23°C through 316°C

		0.1/s			1/s			12/s			150/s		
Temperature [°C]		Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average	Std Dev	COV[%]
23	Ultimate Tensile Strength [MPa]	1,060	12.1	1.14	1095	6.35	0.58	1123	11.60	1.03	1191	9.24	0.78
	0.2% Yield strength [MPa]	1029	12.96	1.26	1071	7.74	0.72	1101	8.81	0.80	1170	6.04	0.52
	Yield strain [%]	1.04	0.01	0.76	1.07	0.01	0.73	1.11	0.01	0.72	1.12	0.01	0.47
	Failure Strength [MPa]	900	12.0	1.33	920	27.6	3.00	928	29.1	3.13	941	37.02	3.93
	Failure Strain [%]	17.0	0.50	2.95	17.2	0.85	4.94	18.0	0.85	4.75	19.2	2.08	10.8
	Modulus [GPa]	122	2.24	1.83	123	1.07	0.87	121	1.48	1.22	127	0.9	0.7
100	Ultimate Tensile Strength [MPa]	974	9.7	0.99	994	10.82	1.09	1024	3.60	0.35	1096	9.61	0.88
	0.2% Yield strength [MPa]	918	14.95	1.63	953	15.00	1.57	988	5.42	0.55	1071	22.82	2.13
	Yield strain [%]	0.98	0.01	0.97	1.00	0.02	1.61	1.04	0.01	0.60	1.06	0.01	0.95
	Failure Strength [MPa]	814	16.4	2.01	816	21.5	2.64	845	20.7	2.45	886	17.60	1.99
	Failure Strain [%]	16.9	0.91	5.39	17.1	0.87	5.07	17.3	0.80	4.64	16.3	1.14	7.0
	Modulus [GPa]	118	0.61	0.51	118	0.96	0.81	118	0.86	0.73	125	3.4	2.7
200	Ultimate Tensile Strength [MPa]	876	-	-	915	-	-	948	12.3	1.30	-	-	-
	0.2% Yield strength [MPa]	-	-	-	-	-	-	898	7.46	0.83	-	-	-
	Yield strain [%]	-	-	-	-	-	-	0.96	0.01	1.38	-	-	-
	Failure Strength [MPa]	717	-	-	756	-	-	773	11.1	1.44	-	-	-
	Modulus [GPa]	-	-	-		-	-	119	0.81	0.68	-	-	-
316	Ultimate Tensile Strength [MPa]	833	5.8	0.69	845	10.51	1.24	860	8.2	0.96	-	-	-
	0.2% Yield strength [MPa]	-	-	-	-	-	-	787	9.10	1.16	-	-	-
	Yield strain [%]	-	-	-	-	-	-	0.86	0.02	2.36	-	-	-
	Failure Strength [MPa]	704	8.0	1.14	691	14.0	2.02	675	20.9	3.09	-	-	-
	Modulus [GPa]	-	-	-		-	-	120	4.73	3.95	-	-	-

Table 3. Summary of Ti 6-2-4-2S Mechanical Properties – 427°C through 650°C

Temperature [°C]		0.1/s			1/s			12/s		
		Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average	Std Dev	COV[%]
427	Ultimate Tensile Strength [MPa]	770	8.0	1.03	768	13.43	1.75	788	14.2	1.81
	Failure Strength [MPa]	667	5.2	0.78	638	16.6	2.60	622	13.6	2.18
538	Ultimate Tensile Strength [MPa]	729	-	-	726	-	-	721	-	-
	Failure Strength [MPa]	627	-	-	611	-	-	580	-	-
600	Ultimate Tensile Strength [MPa]	-	-	-	-	-	-	710	-	-
	Failure Strength [MPa]	-	-	-	-	-	-	565	-	-
650	Ultimate Tensile Strength [MPa]	-	-	-	-	-	-	674	8.8	1.30
	Failure Strength [MPa]	-	-	-	-	-	-	550	18.2	3.32

Table 4. Summary of Ti 6-2-4-2S Elongation, Failure Strain and Reduction in Area

		0.1/s			1/s			12/s			150/s			800/s
Temperature [°C]		Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average	Std Dev	COV[%]	Average
23	Elongation [%]	15.8	1.8	11.60	15.8	1.14	7.22	16.4	1.77	10.8	17.1	2.27	13.3	15.0
	Measured Strain to Failure [%]	17.1	0.53	3.08	17.2	0.85	4.94	18.0	0.85	4.75	19.2	2.08	10.8	-
	Reduction in Area [%]	29.8	2.46	8.27	30.1	2.83	9.41	31.5	2.69	8.55	31.2	3.28	10.5	30.3
100	Elongation [%]	-	-	-	16.2	-	-	-	-	-	15.6	1.61	10.3	-
	Measured Strain to Failure [%]	17.1	0.82	4.80	17.1	0.87	5.07	17.3	0.80	4.64	16.3	1.14	6.98	-
	Reduction in Area [%]	31.5	2.34	7.44	31.7	1.28	4.05	32.4	3.44	10.6	31.9	2.01	6.29	-
200	Elongation [%]	16.8*	-	-	17.5*	-	-	22.9*	-	-	-	-	-	-
	Reduction in Area [%]	39.1	-	-	35.0	-	-	34.8	5.06	14.6	-	-	-	-
316	Elongation [%]	20.5	1.3	6.35	20.8	3.96	19.0	34.0*	-	-	-	-	-	-
	Reduction in Area [%]	36.7	2.79	7.60	37.4	2.60	6.97	36.0	3.63	10.07	-	-	-	-
427	Elongation [%]	23.0	2.1	9.18	24.2	1.59	6.58	22.4	2.1	9.46	-	-	-	-
	Reduction in Area [%]	34.1	4.9	14.29	38.7	3.4	8.69	39.3	3.8	9.66	-	-	-	-
538	Reduction in Area [%]	45.2*	-	-	45.8*	-	-	34.5	-	-	-	-	-	-
600	Reduction in Area [%]	-	-	-	-	-	-	40.3	-	-	-	-	-	-
650	Reduction in Area [%]	-	-	-	-	-	-	37.0	4.0	10.76	-	-	-	-

*Single datum

The rate of increase in the UTS of 37 MPa per decade increase in strain rate was similar at both 23°C and 100°C. There was a 12% increase in the UTS at these two temperatures between 0.1/s and 150/s. The rate effect decreased with temperature – down to 33 MPa per decade at 200°C and 13 MPa/decade at 316°C. There was no significant rate effect at 427°C between 0.1/s and 10/s. The UTS at 538°C and 600°C was equivalent. Rate effects could not be determined for 538°C, 600°C and 650°C due to the limited number of specimens, although it appears that the UTS at 538°C is rate insensitive. The UTS decreased by a factor of 0.6 between 23°C and 650°C at 12/s.

Figure 19 shows the effect of temperature on the UTS at 12/s, showing the expected decrease with increasing temperature. The rate of decrease slowed as the temperature increased.

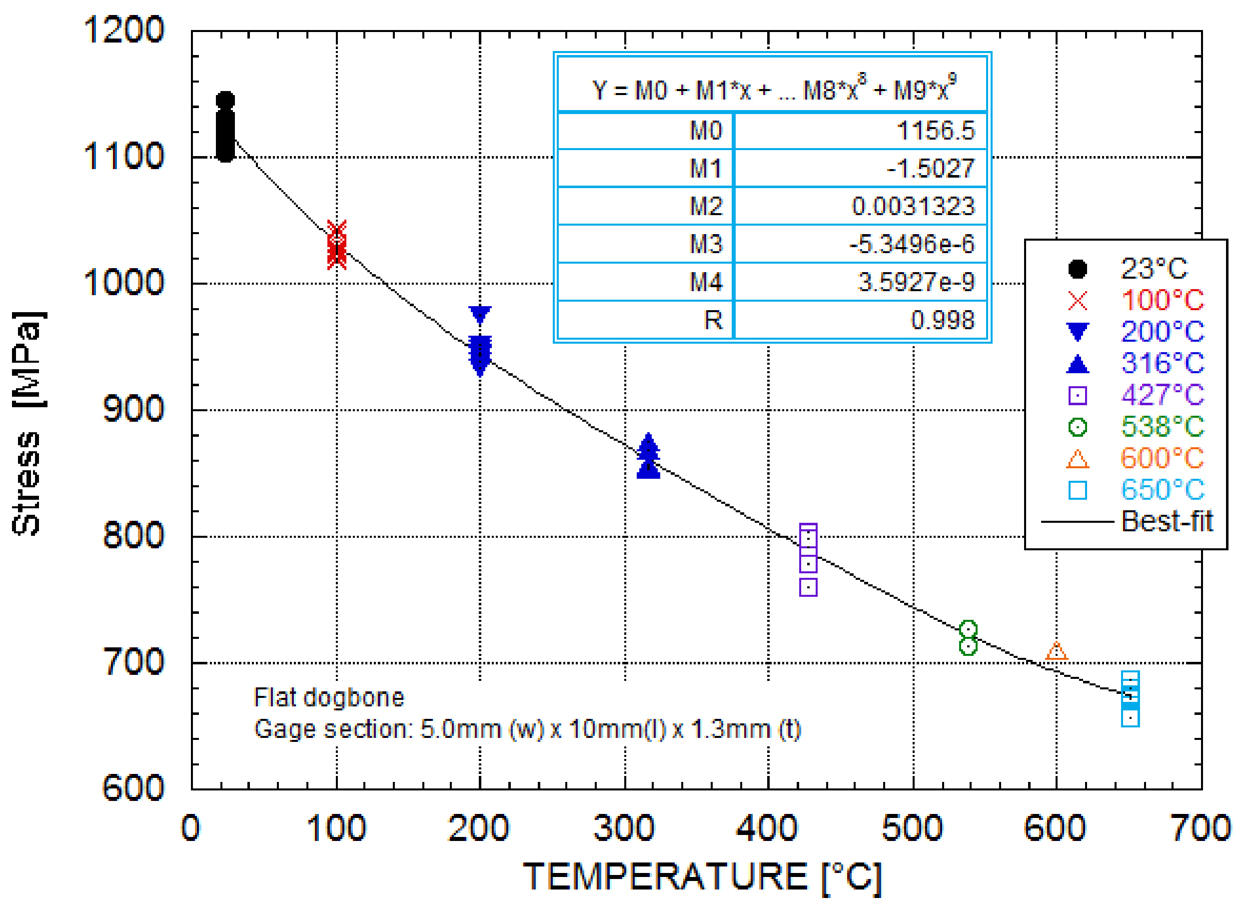


Figure 19. Effect of Increasing Temperature on the UTS of Ti 6-2-4-2S at 12/s

The rate of increase in the yield strength (YS) with rate was slightly higher at 100°C versus 23°C (45 MPa vs. 36 MPa per decade, respectively), which equated to an increase in the YS of 16.6% versus 13.7%, respectively. The YS at 12/s decreased by approximately 100 MPa with each incremental increase in temperature from 23°C to 316°C. The YS decreased by a factor of 0.7 between 23°C and 316°C at 12/s.

The failure stress showed a positive trend with rate at 23°C through 200°C. The trend reversed with rate between 200°C and 316°C, as seen in Figure 15. The rate of increase or decrease ranged from 13 MPa to 35 MPa per decade increase in rate. The failure strength at 538°C, 600°C

and 650°C at 10/s appears to be equivalent. Rate effects could not be determined for 538°C, 600°C and 650°C due to the limited number of specimens.

The failure strain at 23°C and 100°C was not statistically different between 0.1/s and 10/s and showed a slight increase between 150/s and 10/s at 23°C (Figure 16). The elongation and reduction in area (RA) data (Figures 17 and 18, respectively) did not show a clear change with rate, given the scatter and limited data at some temperatures. The effect of temperature on elongation and RA was also unclear. Although it appears that there might be an increasing trend with temperature, the RA data at 650°C overlaps data at the lower temperatures.

7.0 CONCLUSIONS

Quasi-static and high strain rate tension tests were performed on Ti 6-2-4-2S at measured post-yield strain rates of 0.01/s to 150/s and at temperatures ranging from 23°C to 650°C. Data were generated at all temperatures at 12/s.

The UTS increased steadily with rate at 23°C, 100°C, and 200°C, with an increase of 33 to 37 MPa per decade. The increase with rate dropped by half to 13 MPa/decade as the temperature increased from 200°C to 316°C. The UTS appears to be rate insensitive at 427°C and 538°C. The UTS decreased by a factor of 0.6 between 23°C and 650°C at 12/s.

The YS was measured up through 316°C at all of the rates. YS increased 13.7% and 16.6% between 0.1/s and 12/s at 23°C and 100°C, respectively. The YS decreased by a factor of 0.7 between 23°C and 316°C at 12/s.

The failure stress showed a positive trend with rate at 23°C through 200°C. The trend reversed with rate between 200°C and 316°C. The rate of increase or decrease ranged from 13 MPa to 35 MPa per decade increase in rate. The failure strength at 538°C, 600°C and 650°C at 12/s appears to be equivalent. Rate effects could not be determined for 538°C, 600°C and 650°C due to the limited number of specimens.

The failure strain at 23°C and 100°C was not statistically different between 0.1/s and 10/s and showed a slight increase between 150/s and 10/s at 23°C (Figure 16). The elongation and reduction in area (RA) data did not show a clear change with rate, given the scatter and limited data at some temperatures. The effect of temperature on elongation and RA was also unclear. Although it appears that there might be an increasing trend with temperature, the RA data at 650°C overlaps data at the lower temperatures.

APPENDIX A: BACKGROUND ON HIGH-RATE TESTING

The main purpose or goal of quasi-static test methods is to create a relatively large homogeneous stress and strain field. This is usually accomplished by having as large a specimen gage section as possible. Four implicit assumptions are made when reducing the data from these tests: 1) the load is equal in any cross-section of the load train, 2) the strain is equal in the gage section of the specimen, 3) the strain and stress fields are in equilibrium, and 4) the inertial forces are negligible.

The above assumptions must be scrutinized when measuring material properties at high strain rates. Normally, a constitutive equation is thought of as a function relating stresses to the strains at a point (i.e., an infinitesimal volume of material). A quasi-static test assumes that the stress and strain fields are homogeneous in the gage section. The constitutive equation is simply derived from the average response of the tested volume of material.

The wave propagation speed must be considered in a high-rate test. The stress wave propagates along the specimen and is reflected and transmitted at each interface along the line of travel. These interfaces include the transition from grip to specimen, specimen to grip, grip to load washer, etc. As a result, stress waves of varying amplitudes are present in the gage section and a homogeneous stress state does not exist.

The goal in high strain rate tests becomes one of "shocking up" the gage area (i.e., introducing enough stress waves in the gage area so that one can assume that an average stress is present). At best, there is an approximate equilibrium. Since the interest is to find any strain rate dependency in the material properties, it is not necessary to determine the "true" material behavior. Instead, a comparison can be made between the behavior at static rate conditions and the material behavior at higher rates.

High-rate tests dictate the use of a small specimen in order to maximize the number of reflected stress waves along the gage length. If one assumes that specimen geometry will bias the results equally over the range of strain rates used, then one can determine information on the strain rate dependency of the material.

It is critical to analyze the material response from both standard quasi-static and dynamic specimens tested at the same strain rate in order to identify any shape configuration effects. One then makes the assumption that the relative differences due to the specimen configuration are constant across the tested strain rates. The rate effects seen with the smaller specimen are assumed to be representative of the effects one would expect to see on the material properties as measured using the larger quasi-static specimens. For example, the measured ultimate strength using the smaller dynamic specimen may increase 20% over a measured strain rate. One would then assume that the strength data measured using the quasi-static specimen would increase by an equivalent amount over a similar strain rate regime.

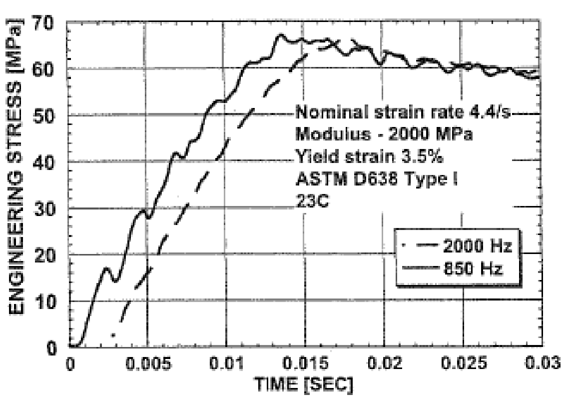
An example of the importance of the natural test frequency is described below. SAE J2749, *High Strain Rate Tensile Testing of Polymers*[5] states that at least 10 to 15 reflected stress waves should be present in the elastic region to generate acceptable yield data. A general equation relating the speed of a stress wave through the test system is given by Eq. A 13 of SAE J2749 as:

$$t_{wave} = 2^*\left[\frac{Lfixt}{vfixt} + \frac{Ldbg}{vm}\right] \qquad \text{(A-1)}$$

where, t_{wave} is the travel time for one stress wave, L_{fixt} is the length of the fixturing, L_{dbg} is the distance between the grips, v_{fixt} is the wave propagation speed through the fixturing, and v_m is the wave propagation speed through the material.

The goal is to minimize t_{wave} so that a high number of waves can propagate through the material and fixturing. At some test speed, the time scale for t_{wave} will approach that of the time required to propagate 10 to 15 waves through the specimen gage length before a 0-.2% offset is reached. Discrete stress waves will be observed on the material response.

The v_m is fixed for a given test. The v_{fixt} is dependent on the fixturing material. Most high-rate fixtures are made of metal. The wave propagation speed of most metals is 4000 to 5000 m/s and altering the fixture metal offers relatively little improvement. The terms which can be easily modified thorough fixture and specimen design are L_{fixt} and L_{dbg}. Minimizing the specimen length and, hence, the fixture length and weight, is a key component for a successful high-rate test system. Figure A-1 illustrates the difference in output one can expect by simply from changing the fixture length and weight and, thus, the natural resonant frequency.



Curves shifted along the time axis for ease of comparison. Reference Figure A3 of SAE J2749

Figure A1. Difference in the Measured Response for Test Systems with Different Natural Resonant Frequencies

Typical quasi-static specimens are relatively large with gage lengths ~2.25" [56 mm] and overall lengths of 6.0" [154 mm] or longer. Testing a large specimen at high rates introduces several

[5] SAE J2749, "Surface Vehicle Recommended Practice – High Strain Rate Tensile Testing of Polymers," SAE International, 400 Commonwealth Drive, Warrendale, PA 15096, www.sae.org.

issues, namely, equipment capacity due to the higher failure loads, proper load introduction into the material before failure, achieving dynamic equilibrium within the timeframe of the test event, and natural oscillatory vibrations within the specimen and test system.

High-quality data at rates above 1 to 10/s require smaller specimens with short gage lengths. The small specimen size needed to achieve the high rates is usually in direct conflict with the size needed to represent bulk material properties. The final specimen size is often a compromise between the requirements to achieve a high rate and the need to determine relative rate effects on the measured properties.

APPENDIX B: PROCEDURE FOR CLEANING TITANIUM

Titanium test specimens need to be cleaned prior to coating, painting, or instrumentation. Excess machining oils are left in the titanium from manufacture. The excess oil will prevent a firm bond between the coating, painting, or instrumentation weld and the titanium surface.

Prepare the cleaning area, having a piece of clean sheet metal placed on a table. The following items will also be needed:

1. Oven mitts
2. Isopropyl alcohol (in a squeeze bottle)
3. Acetone (in a squeeze bottle)
4. 7448 and 8447 3M Scotch Brite cleaning pads (cut into 2x4 inch rectangles)
5. Clean cotton gauze pad (will need a generous amount)
6. Trash can

Begin by preparing the oven for mild heating. The oven is held constant at 350°F. Do not directly set the oven to maximum temperature; it must be stepped up from 250°F before changing to the final temperature of 350°F. While the oven is preheating, all titanium samples are to be wiped clean on all sides with a fresh cotton gauze pad and isopropyl alcohol to remove any oils on the surface. Once the oven is at temperature, all specimens are placed inside the oven on a steel rack. Wait no less than 30 minutes for the specimens to get to temperature.

While wearing oven mitts, quickly and carefully remove one specimen from the oven and close the door to the oven. Quickly place the specimen on the sheet metal on top of the table. Spray acetone over the entire surface of the hot titanium. Scrub the specimens with the 7448 (maroon) Scotch-Brite pads while spraying acetone onto the specimen. Continue spraying and scrubbing until the acetone stops instantly evaporating. A black residue should be left on the titanium sample. Spray the specimen with isopropyl alcohol to suspend the oil and residue left from scrubbing. Using a clean gauze pad, clean the specimen thoroughly. Repeat cleaning with fresh gauze and isopropyl alcohol until the gauze is clean (no black residue is removed). After this is complete, place the article back into the oven, flipping the side on which it was laying. Heat the article for thirty (30) minutes before removing it to clean again. Continue this process until all specimen sides have been through two complete cleaning cycles with 7448 Scotch-Brite. On the last cleaning cycle, use the 8447 (gray) Scotch-Brite cleaning pad. Each specimen side should go through a total of three cycles per side: heating the specimen, scrubbing with acetone, and cleaning with isopropyl.

APPENDIX C: TEST EQUIPMENT & STRAIN GAGE CALIBRATIONS

Testing Equipment Information	
Goekel_High temp Tensile Station #31	LB9021
Testing laboratory: SMART Lab	Point of contact: John Chumack
Telephone/Fax: 937-229-4426	Address:
Test machine information	
Manufacturer: MTS 2 Poster Frame & controller	Manufacturer's reference number: 407.14 Station #31
Maximum capacity (test machine): 11 Kip	Machine type (servo-hydraulic / servo-electric): S-H
Maximum capacity (load cell): 10K , set for 5K ra	Method of data acquisition: LabView GPTC
Range load cell used: LC #1432 = 2k or 2000lb ra	Filtering (if applicable):
Comments:Load Cell Sn#1432, Calibration date 04DEC15 - shunt cal check 03May16	
MTS 11kip actuator model #204.61, sn#375, +-2.5"stroke	
Gripping information	
Type of grip: Inconel 718 Grips	Type of loading (tab, shoulder): Shoulder loaded
Manufacturer: UDRI	Method of specimen alignment in grip:
Manufacturer's reference number:	Visual & Dial Indicator
Surface type/finish:	Self aligning load train or grip (if applicable):
Wedge angle (if applicable):	Titanium Rod, Slack Adapter
Comments: Short Grip on top to allow for Flame spray gage wires	
Instrumentation information	
Calibration/verification dates: 30Dec2015 & 8Feb2016	Data disk/filename: see Cal sheet 03/07
Method of calibration: Static Standard Cell and Gaged Blocks/dial indicator for LVDT Check	Data sampling rate: see Cal sheet 03/07
LVDT Cal check date =25Jul12 +-2.5" stroke Actuator, see Cal sheet 02/37	
Comments:	
Frequency response	
Component 1: DVM Kiethely 175 SN#409294	
Component 2: DAQ PC = RC 11141 with NI 6024E	
Component 3:	
Component 4:	
Component 5:	
Overall frequency response:	
Ancillary equipment (please list and describe usage)	
GPTC Program version 03b	
National Instruments Data Capture Card, PCI -6024E & BNC 2110 RC11312 PC	
Micro Measurements Strain gages WK-062AP-350, EP-08-062AP120, HFP-12-125-SPW	
Vishay 2311 Amplifiers SN# 108525 & 108506	
Dantec Dyanmics Q400 low speed imaging system, 17mm lens	
Dantec Dynamics Q450 high speed DIC 3D Imaging Camera system 100mm lenses & 3x extentions	
Marker type = UDRI Paint pattern with spray can	
Omega Thermal Couple reader UD 11/07 DP116-KF1-DSS, sn# 4421338-1 K type	
NI SCXI 1001 Thermal Couple Controller & 1303 Module UDRI Calibration Code CC001E, cal date 5/3/16	
110 ATS High temp Furnace - Max 1650F, range used 392F to 1202 F, Series 32, sn#00-1334	
Staco Energy Variac 10Amp, 120v, type 3PN1010, SN# 122-0003	
UDRI DAQMX Logger Software 0.1.3	
2 Deeda cool Lights, & 2 Fiber optics Lights,	
National Instruments Data Capture Card, PCI -6024E & BNC 2110 RC11312 PC	

Testing Equipment Information	
Station# 6	
Goekel_AFRL_High Rate Tensile Program	LB9021
Testing laboratory: SMART Lab	Point of contact: John Chumack
Telephone/Fax: 937-229-4426	Address:
Test machine information	
Manufacturer: MTS 4 Poster Frame	Manufacturer's reference number:MTS 458.10 Controller # 6
Maximum capacity (test machine): 3 Kip 10"	Machine type (servo-hydraulic / servo-electric): S-H
Maximum capacity (load cell): FW 20K	Method of data acquisition: LabView HSDAQ 10MHZ
Range load cell used:FW = 2K, calibrated	Filtering (if applicable):
Comments: Dynamic Cal FW vs. Load Cell# 2500 Station#4 @ 5hz	
MTS 458.10 Controller & MicroProfiler 458.91 Program # 11	
MTS 3.3kip actuator 204.51sn#236 10.5" stroke LVDT Transtec #0219-0001 Cal +-5 inch, 90GPM valve	
Kistler Force Washer model 9041A, 20K, 1407424, Kistler FW Amp sn#3223 500lb, 1K, 2K, 5K ranges	
Gripping information	
Type of grip: D638 type 5 , 5mil Steel Grip for top	Type of loading (tab, shoulder):Shoulder Loaded
Manufacturer: UDRI	Method of specimen alignment in grip:
Manufacturer's reference number: UDRI 5MM & Inconel 718	Visual & Dial Indicator sn# 25-5041
Surface type/finish: Black Anodized	Self aligning load train or grip (if applicable):
Wedge angle (if applicable):	Self aligning slack Adapter
Comments: Aluminum Slack Adapter with Titanium Rod, steel Cone, Black Oring, Grease	
Instrumentation information	
Calibration/verification dates: FW 06Jun16	Data disk/filename: cal record # 02/09 & 03/24
Method of calibration: Dynamic	Data sampling rate:
FW calibrated to Standard Cell 03/04 SN# 2500 station#4	
Comments: LVDT Cal date = 1 APR 16	
Frequency response	
Component 1: Dantec DIC PC System	
Component 2: 2311 Amplifiers SN#108525	
Component 3: 2311 Amplifiers SN#108506	
Component 4: DVM Kiethely 175 SN#249078	
Component 5:	
Ancillary equipment (please list and describe usage)	
Kistler FW 9041A Sn# 1407424	
National Instruments HSDAQ Data Capture Card, PCI -6115 & BNC 2110 SMEG-01 PC	
FW Kistler Amplifier 5010 sn#160525	
HSDAQ Software 03b.vi	
Micro Measurements Strain gages WK-062AP-350, EP-08-062AP120, HFP-12-125-SPW	
Vishay 2311 Amplifiers SN# 108525 & 108506	
Dolen Jenning Fiber Optic lights(2) & Deedacool Lights(2)	
Dantec Q450 high speed DIC 3D Imaging Camera system 100mm lenses & 3x extentions	
Marker type = UDRI Paint pattern with spray can	
Omega Thermal Couple reader UD 11/07 DP116-KF1-DSS, sn# 4421338-1 K type	
NI SCXI 1001 Thermal Couple Controller & 1303 Module UDRI Calibration Code CC001E, cal date 5/3/16	
110 ATX High temp Furnace - Max 1650F, range used 392F to 1202 F, Series 32, sn#00-1334	
Staco Energy Variac 10Amp, 120v, type 3PN1010, SN# 122-0003	
UDRI Clear optical Window Mini Heat Chamber for 212F tests	
UDRI DAQMX Logger Software 0.1.3	

####### 8:50 AM

Strain Gage Calibration Worksheet

Full Scale Strain (ue)	Full Scale Voltage (volts)	Gage Resistance (ohms)	Gage Factor	***MEASURED*** Calibration Resistance (ohms)
50,000	10	350	2.01	4,220

R(c) = R / ((G * e) * (1 - (G * e))) = 3,872

e(c) = -R / (G * (R + R(c)) = -0.038102703

V(c) = -(e(c) / e(FS)) * V(FS) = **7.621**

Notes: Gage type: WK-06-062AP-350
Tensile Flat Dogbone LB9021
Susan Hill
392°F to 600°F

####### 8:42 AM

Strain Gage Calibration Worksheet

Full Scale Strain (ue)	Full Scale Voltage (volts)	Gage Resistance (ohms)	Gage Factor	***MEASURED*** Calibration Resistance (ohms)
20,000	10	120	4.05	1,615

R(c) = R / ((G * e) * (1 - (G * e))) = 1,612

e(c) = -R / (G * (R + R(c)) = -0.017077596

V(c) = -(e(c) / e(FS)) * V(FS) = **8.539**

Notes: Gage type: HFP-12-125-SPW
Tensile flat Dogbone LB9021
S. Hill
Flame spray gages
800°F to 1200°F only
2% full scale
Boron nitride spray for grips

####### 9:00 AM

Strain Gage Calibration Worksheet

Full Scale Strain (ue)	Full Scale Voltage (volts)	Gage Resistance (ohms)	Gage Factor	***MEASURED*** Calibration Resistance (ohms)
50,000	10	120	4.05	678

R(c) = R / ((G * e) * (1 - (G * e))) = 743

e(c) = -R / (G * (R + R(c)) = -0.037129862

V(c) = -(e(c) / e(FS)) * V(FS) = **7.426**

Notes: Gage type: HFP-12-125-SPW
Tensile Flat Dogbone LB9021
Susan Hill

Flame spray gages
1200°F
5% full scale
Used on 397-110 and 397-104

APPENDIX D: DIC POLYGON SIZES AND STRAIN LIMTS

DIC POLYGON SIZES

	GLOBAL POLYGON SIZE*		LOCAL POLYGON SIZE*	
SPECIMEN ID	LENGTH [MM]	WIDTH [MM]	LENGTH [MM]	WIDTH [MM]
397-50	9.10	2.96	1.86	2.96
397-52	9.17	3.15	1.02	3.15
397-53	9.13	3.58	1.12	3.58
397-54	9.12	3.52	1.12	3.52
397-55	9.26	3.74	1.25	3.74
397-56	9.39	3.50	1.45	3.50
397-57	9.16	3.55	1.15	3.55
397-58	9.30	3.65	1.48	3.65
397-59	9.33	3.37	1.25	3.37
397-60	9.33	3.35	1.29	3.35
397-63	9.29	3.70	1.65	3.70
397-64	9.27	3.40	1.22	3.40
397-65	9.29	3.21	1.15	3.21
397-66	9.19	3.59	1.38	3.59
397-67	8.76	3.53	1.55	3.53
397-68	9.12	3.39	1.09	3.39
397-69	9.29	3.51	1.12	3.51
397-83	9.02	3.32	2.07	3.32
397-85	9.06	3.11	1.95	3.11
397-86	9.25	3.15	1.79	3.15
397-87	9.30	3.36	1.92	3.36
397-88	8.97	3.48	1.57	3.48
397-89	9.00	3.07	1.67	3.07
397-90	9.01	1.51	2.95	1.51
397-91	9.25	2.91	1.82	2.91
397-92	9.16	1.89	2.88	1.89
397-93	8.94	2.97	1.57	2.97
397-94	8.97	3.18	1.54	3.18
397-95	9.07	3.14	1.45	3.14
397-96	8.97	2.92	1.48	2.92
397-97	8.99	1.32	3.10	1.32
397-170	9.80	3.19	2.06	3.19
397-171	8.10	3.18	1.66	3.18
397-172	8.55	3.33	1.54	3.33
397-173	7.61	3.27	1.73	3.27
397-181	8.75	2.90	1.44	2.90
397-182	8.75	2.97	1.74	2.97
397-183	8.82	3.32	1.82	3.32
397-184	8.94	3.12	1.48	3.12
397-185	8.71	3.17	1.89	3.17
397-186	8.67	3.17	1.66	3.17
397-187	8.76	3.17	1.60	3.17
397-190	9.21	3.25	1.67	3.25
397-191	8.84	3.42	1.78	3.42
397-192	8.95	3.13	1.62	3.13
AVERAGE	9.02	3.17	1.64	3.17

*Length is equivalent to the gage length

DIC STRAIN MEASUREMENT LIMITS

	Measured Limit for Valid DIC strain		Extrapolated Failure Strain	
SPECIMEN ID	Global Strain [%]	Local Strain [%]	Global Strain [%]	Local Strain [%]
397-50	12.0	25.0	15.9	33.9
397-52	16.7	39.2	-	-
397-53	17.0	37.4	-	-
397-54	16.5	37.8	16.5	37.8
397-55	16.7	35.1	16.8	35.2
397-56	17.7	38.2	-	-
397-57	17.6	41.3	-	-
397-58	16.6	35.6	16.7	36.1
397-59	18.2	40.3	-	-
397-60	17.3	39.3	17.4	39.8
397-63	17.5	38.2	17.6	38.6
397-64	16.0	36.8	16.0	37.1
397-65	17.6	45.7	-	-
397-66	17.3	39.9	-	-
397-67	19.5	52.7	-	-
397-68	17.8	44.4	-	-
397-69	17.8	42.0	-	-
397-83	13.4	21.7	16.5	36.0
397-85	13.0	21.1	17.1	37.9
397-86	16.3	-	16.6	-
397-87	14.8	21.5	18.3	35.8
397-88	13.6	28.4	16.3	41.0
397-89	16.8	29.2	18.5	37.2
397-90	14.4	26.6	16.9	40.2
397-91	14.5	25.5	17.2	40.4
397-92	14.3	24.1	16.5	33.7
397-93	17.4	34.6	18.4	38.7
397-94	17.5	36.4	-	-
397-95	16.4	34.6	17.0	37.5
397-96	15.8	37.9	16.2	40.0
397-97	16.4		17.3	42.2
397-170	16.7	32.9	17.7	37.2
397-171	STRAIN DATA SUSPECT		-	-
397-172	18.3	34.9	18.8	36.7
397-173	-	-	23.6	39.4
397-181	18.3	39.9	18.9	42.8
397-182	18.7	36.6	19.2	39.5
397-183	17.3	35.0	17.8	35.3
397-184	16.9	35.3	17.2	37
397-185	20.0	-	20.8	-
397-186	17.6	-	18.1	-
397-187	16.7	16.7	42.0	42.0
397-190	-	-	-	-
397-191	14.8	34.8	15.8	39.9
397-192	15.0	34.5	15.7	33.6

APPENDIX E: MECH PROPS & SUMMARY GRAPHS – 23°C

Table E1. Mechanical Properties of Ti 6-2-4-2S at 0.1/s and 23°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages and digital image correlation (DIC).

23°C Ambient humidity	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 0.1/s	1/12/16	397-01	1,038	1,007	1.04	879	-	-	121	1.12	0.112	0.0964	0.0936	2-4.1	
	1/4/16	397-04	1,065	1,034	1.03	893	-	-	124	1.11	0.111	0.0947	0.0916	2-4.8	
	1/12/16	397-06	1,031	1,002	1.04	883	-	-	119	1.12	0.112	0.0890	0.0869	2-2.6	
	1/12/16	397-07	1,066	1,033	1.03	907	-	-	124	1.12	0.112	0.0900	0.0869	2-5	
	1/12/16	397-12	1,055	1,022	1.02	894	-	-	124	1.11	0.111	0.0979	0.0965	1.6-2	
Average			***1,051***	***1,019***	***1.03***	***891***			***122***						
Std.Dev.			***15.8***	***14.50***	***0.01***	***11.2***			***2.2***						
Coeff. of Var. [%]			***1.50***	***1.42***	***0.6***	***1.25***			***1.8***						
DIC and Un-instrumented 0.1/s	2/8/16	397-52	1,064	1,037	1.05	909	39.2	16.7	126	1.11	0.111	0.0971	0.0928	2-7	
	2/8/16	397-53	1,064	1,035	1.04	907	37.4	17.0	123	1.11	0.111	0.0967	0.0924	2-7	
	2/8/16	397-54	1,066	1,035	1.05	909	37.8	16.5	123	1.11	0.111	0.0979	0.0936	2-7	
	2/9/16	397-55	1,065	1,035	1.05	917	35.2	16.8	123	1.11	0.111	0.0960	0.0917	2-7	
	2/10/16	397-56	1,068	1,037	1.05	888	38.2	17.7	124	-	-	0.0955	0.0913	2-7	DAQ stroke data lost
	2/10/16	397-57	1,070	1,041	1.05	900	41.3	17.6	123	1.12	0.112	0.0965	0.0923	2-7	
	12/30/15	397-45	1,068	-	-	914	-	-	-	1.12	0.112	-	-	-	
	12/30/15	397-46	1,065	-	-	901	-	-	-	1.12	0.112	-	-	-	
Average			***1,066***	***1,037***	***1.05***	***906***	***38.2***	***17.0***	***124***						
Std.Dev.			***2.13***	***2.28***	***0.002***	***9.18***	***2.02***	***0.50***	***1.27***						
Coeff. of Var. [%]			***0.20***	***0.22***	***0.2***	***1.01***	***5.29***	***2.95***	***1.03***						
Average [overall]			***1,060***	***1,029***	***1.04***	***900***									
Std.Dev.			***12.1***	***13.0***	***0.01***	***12.0***									
Coeff. of Var. [%]			***1.14***	***1.26***	***0.76***	***1.33***									

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table E2. Mechanical Properties of Ti 6-2-4-2S at 1/s and 23°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness

Strain measured with gages and digital image correlation (DIC).

23°C Ambient humidity	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 1/s	1/12/16	397-08	1,089	1,065	1.06	965	-	-	123	11.2	1.12	1.12	1.08	2-5	
	1/12/16	397-10	1,091	1,068	1.06	918	-	-	124	11.3	1.13	1.06	1.03	2-4.6	
	1/15/16	397-15	1,084	1,060	1.07	926	-	-	121	11.2	1.12	1.11	1.08	2-3	
	1/12/16	397-17	1,087	1,062	1.07	922	-	-	124	11.2	1.12	1.03	0.997	2-5	
	1/15/16	397-20	1,093	1,072	1.06	909	-	-	122	11.3	1.13	1.01	0.984	2-2.2	
Average			***1,089***	***1,065***	***1.07***	***928***			***123***						
Std.Dev.			***3.5***	***4.71***	***0.01***	***21.6***			***1.1***						
Coeff. of Var. [%]			***0.32***	***0.44***	***0.5***	***2.33***			***0.9***						
DIC and Un-instrumented 1/s	2/10/16	397-58	1,100	1,077	1.08	919	36.1	16.7	121	11.2	1.12	1.02	0.975	2-7	
	2/10/16	397-59	1,096	1,074	1.08	904	40.3	18.2	122	11.2	1.12	1.02	0.977	2-7	
	2/10/16	397-60	1,098	1,075	1.08	894	39.8	17.4	117	11.2	1.12	1.02	0.975	2-7	
	2/10/16	397-63	1,097	1,075	1.08	884	38.6	17.6	119	11.2	1.12	1.03	0.987	2-7	
	2/10/16	397-64	1,106	1,086	1.08	978	37.1	16.0	120	11.1	1.11	1.07	0.982	2-7	
	2/9/16	397-61	1,095	-	-	896	-	-	-	11.2	1.12		-	-	DIC data lost
	1/11/16	397-47	1,101	-	-	925	-	-	-	11.0	1.10	-	-	-	
Average			***1,099***	***1,077***	***1.08***	***914***	***38.3***	***17.2***	***120***						
Std.Dev.			***3.60***	***4.77***	***0.004***	***31.47***	***1.76***	***0.85***	***2.22***						
Coeff. of Var. [%]			***0.33***	***0.44***	***0.4***	***3.44***	***4.59***	***4.94***	***1.85***						
Average [overall]			***1,095***	***1,071***	***1.07***	***920***									
Std.Dev.			***6.3***	***7.7***	***0.0***	***27.6***									
Coeff. of Var. [%]			***0.58***	***0.72***	***0.73***	***3.00***									

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table E3. Mechanical Properties of Ti 6-2-4-2S at 10/s and 23°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages and digital image correlation (DIC).

23°C Ambient humidity	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 10/s	1/15/16	397-09	1,126	1,104	1.11	950	-	-	122	124	12.4	11.8	11.6	2-2.8	
	1/15/16	397-13	1,114	1,091	1.11	927	-	-	119	124	12.4	12.4	12.1	2-2.9	
	1/15/16	397-16	1,128	1,104	1.11	943	-	-	121	122	12.2	12.6	12.3	2-2.9	
	1/15/16	397-18	1,119	1,099	1.11	941	-	-	122	124	12.4	-	-	-	
	1/15/16	397-19	1,127	1,100	1.10	950	-	-	123	124	12.4	13.0	12.6	2-2.8	
Average			***1,123***	***1,099***	***1.11***	***942***			***121***						
Std.Dev.			***5.8***	***5.40***	***0.01***	***9.5***			***1.5***						
Coeff. of Var. [%]			***0.52***	***0.49***	***0.6***	***1.00***			***1.2***						
DIC and Un-instrumented 10/s	2/10/16	397-65	1,107	1,083	1.09	874	45.7	17.6	114	124	12.4	12.5	11.9	2-7	
	2/10/16	397-66	1,130	1,110	1.12	918	39.9	17.3	123	125	12.5	11.9	12.5	2-7	
	2/10/16	397-67	1,131	1,110	1.12	881	52.7	19.5	122	124	12.4	12.6	12.0	2-7	
	2/10/16	397-68	1,126	1,105	1.11	892	44.4	17.8	119	124	12.4	12.5	11.9	2-7	
	2/10/16	397-69	1,130	1,108	1.11	921	42.0	17.8	117	124	12.4	12.4	11.9	2-7	
	1/11/16	397-48	1,145	-	-	951	-	-	-	124	12.4	-	-	-	
	6/8/16	397-102	1,104	-	-	963	-	-	-	119	11.9	-	-	-	Note 1
	6/8/16	397-116	1,108	-	-	950	-	-	-	78.7	7.87	-	-	-	Note 2
Average			***1,123***	***1,103***	***1.11***	***919***		***18.0***	***119***						
Std.Dev.			***14.5***	***11.68***	***0.010***	***34.01***		***0.85***	***3.66***						
Coeff. of Var. [%]			***1.29***	***1.06***	***0.9***	***3.70***		***4.75***	***3.07***						
Average [overall]			***1,123***	***1,101***	***1.11***	***928***									
Std.Dev.			***11.6***	***8.8***	***0.01***	***29.1***									
Coeff. of Var. [%]			***1.03***	***0.80***	***0.72***	***3.13***									

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Note 1. Trial run using flame sprayed gages. Strain data not valid. Cycled up through 480 Mpa eight times before final test to failure.

Note 2 Flame sprayed gaged. Strain data not valid.

Table E4. Mechanical Properties of Ti 6-2-4-2S at 150/s to 1000/s and 23°C

23°C Ambient humidity	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 150/s	6/22/16	397-3	1,150	1,130	1.10	955	-	-	126	1762	176	177.90	171.26	3-4.8	
	6/22/16	397-5	1,151	1,132	1.09	944	-	-	127	1766	177	182.15	175.33	3-4.8	
	6/22/16	397-11	1,149	1,132	1.10	940	-	-	126	1764	176	180.13	173.49	3-4.7	
	6/22/16	397-43	1,159	1,143	1.09	953	-	-	128	1764	176	169.67	163.76	2.8-4.5	
	6/22/16	397-44	1,157	1,139	1.10	958	-	-	127	1763	176	177.63	171.17	3-4.8	
Average			***1,153***	***1,135***	***1.10***	***950***			***127***						
Std.Dev.			***4.5***	***5.54***	***0.00***	***7.9***			***0.9***						
Coeff. of Var. [%]			***0.39***	***0.49***	***0.4***	***0.83***			***0.7***						
DIC and Un-instrumented 150/s	6/28/16	397-181	1,187	1,165	1.12	871	42.8	18.9	121	1847	185	146	141	2-6	
	6/28/16	397-182	1,197	1,178	1.13	920	39.4	19.2	119	1849	185	150	145	2-6	stress waves
	6/28/16	397-183	1,190	1,170	1.12	973	35.3	17.8	116	1843	184	147	142	2-6	
	6/28/16	397-184	1,189	1,166	1.12	989	37.1	17.2	116	1862	186	148	143	2-6	
	6/28/16	397-185	1,192	-	-	877	-	20.8	119	1848	185	150	145	2-6	stress waves
	6/23/16	397-170	1,190	-	-	965	37.2	17.7	-	1727	173	153	146	2-6	stress waves
	6/23/16	397-171	1,186	-	-	910	-	-	-	1767	177	-	-	2.4-6.4	stress waves. DIC strain data suspect
	6/23/16	397-172	1,178	-	-	962	36.7	18.8	125	1781	178	109	105	2.2-6.2	
	6/23/16	397-173	1,175	-	-	906	39.4	23.6	126	1773	177	92.9	95.0	2.2-6.2	stress waves
	6/22/16	397-14	1,194	-	-	975	-	-	-	1799	180	-	-		
	6/16/16	397-169	1,190	-	-	946	-	-	-	1695	169	-	-		stroke slowdown towards UTS
	6/28/16	397-176	1,205	-	-	960	-	-	-	1836	184	-	-		
	6/28/16	397-177	1,209	-	-	982	-	-	-	1845	185	-	-		
	6/17/16	379-179	1,184	-	-	937	-	-	-	2401	240	-	-		higher amp stress waves
	6/17/16	379-180	1,201	-	-	942	-	-	-	2396	240	-	-		higher amp stress waves
Average			***1,191***	***1,170***	***1.123***	***941***		***19.2***	***120***						
Std.Dev.			***9.24***	***6.04***	***0.005***	***37.02***		***2.08***	***3.94***						
Coeff. of Var. [%]			***0.78***	***0.52***	***0.5***	***3.93***		***10.80***	***3.28***						
IB 1000/s	12/30/15	397-51	1,217	-	-	1,005	-	-	-	10,181	1,018	-			
	12/30/15	397-62	1,123	-	-	1,055	-	-	-	10,128	1,013	-			
Average			***1,170***												

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table E5. Reduction in Area Measurements of Ti 6-2-4-2S at 23°C

Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Measured Strain(2) to Failure [%]	Reduction in Area [%]
0.1	397-01	-	-	35.5
	397-04	-	-	29.9
	397-06	-	-	29.9
	397-07	-	-	32.0
	397-12	-	-	28.0
	397-45	15.5	-	26.2
	397-46	1.31*	-	27.4
	397-52	-	-	31.2
	397-53	-	17.0	28.2
	397-54	-	16.5	29.8
	397-55	13.4	16.8	27.9
	397-56	17.8	17.7	31.8
	397-57	16.3	17.6	29.1
	Average	***15.8***	***17.1***	***29.8***
	Standard Deviation	***1.8***	***0.5***	***2.5***
	Coeff of Variation [%]	***11.6***	***3.1***	***8.3***
1	397-08	-	-	27.6
	397-10	-	-	31.9
	397-15	-	-	31.6
	397-17	-	-	23.1
	397-20	-	-	34.4
	397-47	16.9		29.5
	397-58	15.1	16.7	29.8
	397-59	15.5	18.2	30.1
	397-60	17.6	17.4	31.3
	397-61	15.8	-	30.2
	397-63	15.8	17.6	32.4
	397-64	14.1	16.0	28.9
	Average	***15.8***	***17.2***	***30.1***
	Standard Deviation	***1.1***	***0.8***	***2.8***
	Coeff of Variation [%]	***7.2***	***4.9***	***9.4***

Note 1 Average measured strain rate.
Note 2 Using digital image correlation
* Excluded point from average

Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Measured Strain(2) to Failure [%]	Reduction in Area [%]
12	397-09	-	-	37.0
	397-116	-	-	28.4
	397-13	-	-	31.6
	397-16	-	-	28.4
	397-18	-	-	28.1
	397-19	-	-	31.6
	397-48	17.4	-	28.6
	397-65	15.6	17.6	33.2
	397-66	15.4	17.3	32.9
	397-67	13.7	19.5	32.3
	397-68	17.6	17.8	32.6
	397-69	18.5	17.8	33.3
	Average	***16.4***	***18.0***	***31.5***
	Standard Deviation	***1.8***	***0.9***	***2.7***
	Coeff of Variation [%]	***10.8***	***4.7***	***8.5***
150	397-03	-	-	25.9
	397-05	-	-	33.7
	397-11	-	-	30.0
	397-14	-	-	35.2
	397-169	16.8	-	32.7
	397-170	15.7	17.7	36.4
	397-171	19.3	-	28.4
	397-172	19.5	18.8	26.8
	397-173	21.8	23.6	29.1
	397-176	14.8	-	30.7
	397-177	14.4	-	28.2
	397-179	15.1	-	29.2
	397-180	16.5	-	30.2
	397-181	18.6	18.9	34.5
	397-182	18.7	19.2	36.5
	397-183	16.8	17.8	32.9
	397-184	14.8	17.2	27.6
	397-185	9.44*	20.8	32.4
	397-43	-	-	34.8
	397-44	-	-	28.5
	Average	***17.1***	***19.2***	***31.2***
	Standard Deviation	***2.3***	***2.1***	***3.3***
	Coeff of Variation [%]	***13.3***	***10.8***	***10.5***
804	397-62	15.9	-	30.7
	397-51	14.1	-	30.0
	Average	***15.0***		***30.3***

Note 1 Average measured strain rate.
Note 2 Using digital image correlation
* Excluded point from average

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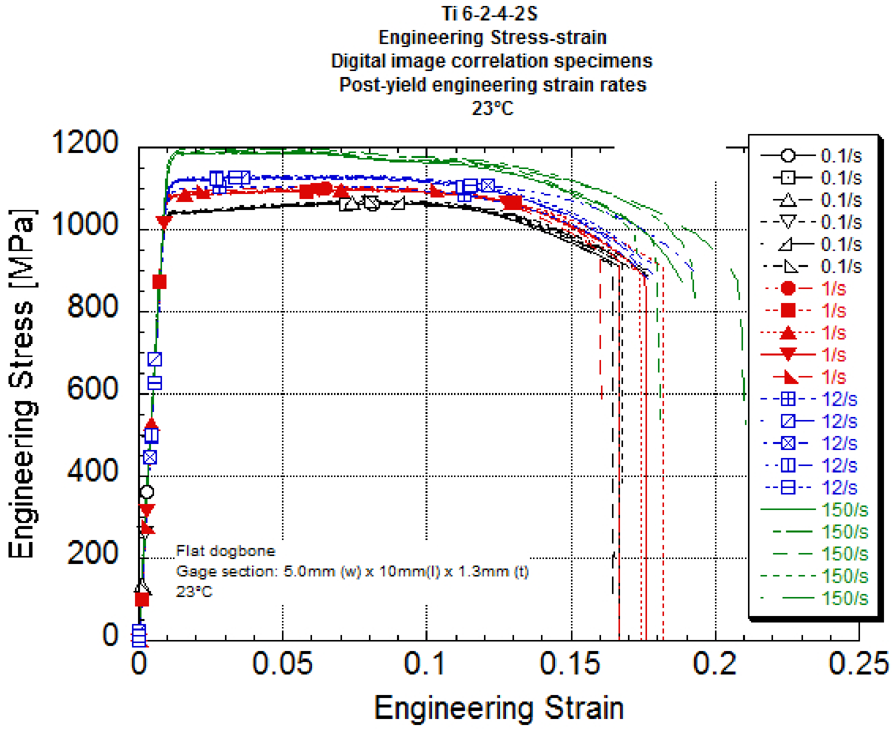
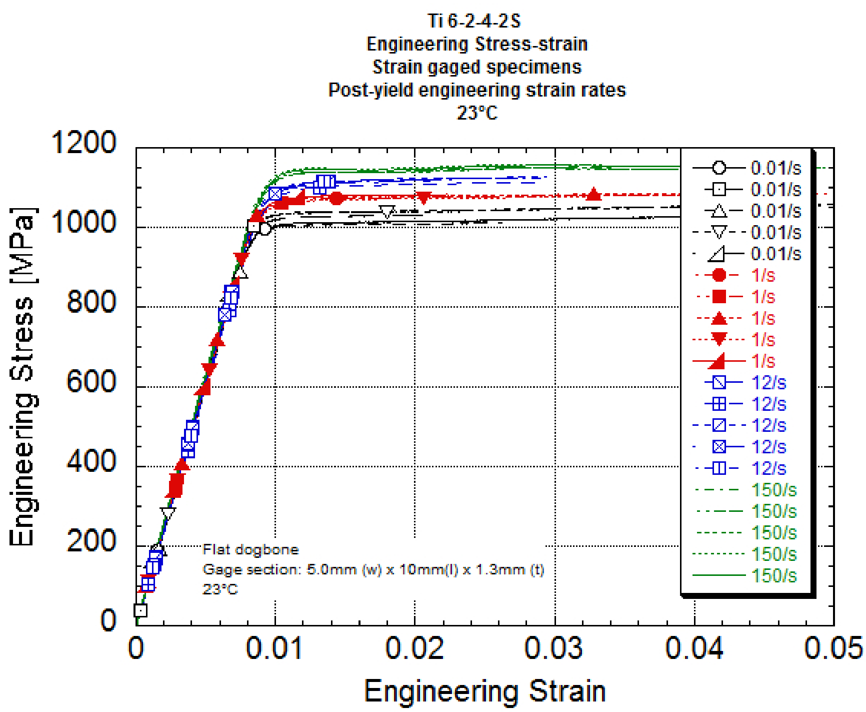
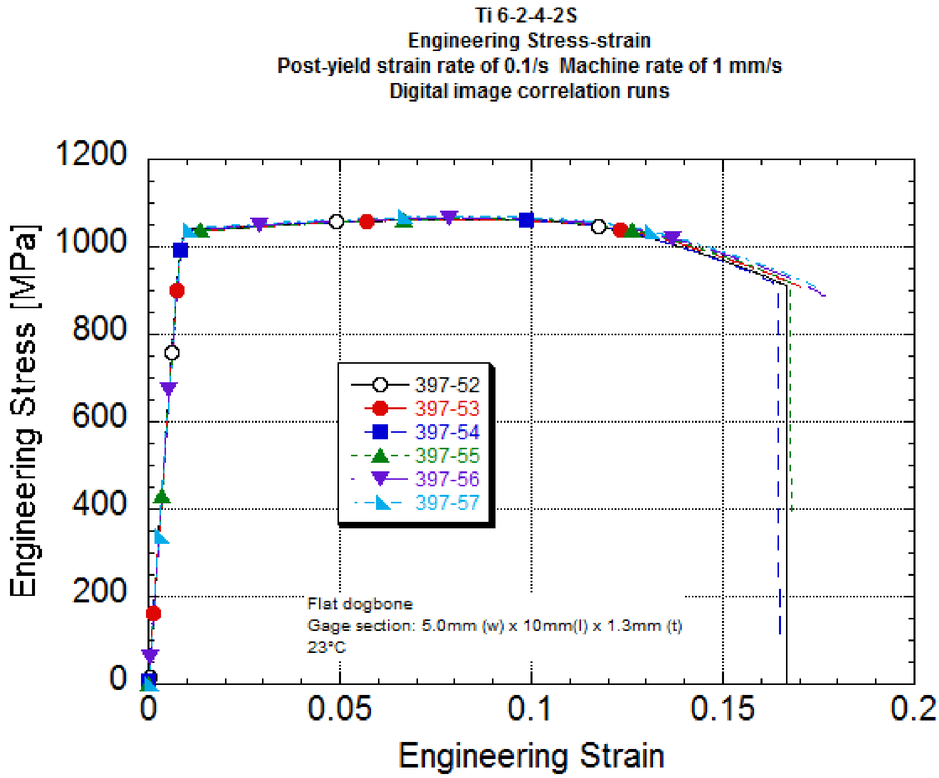
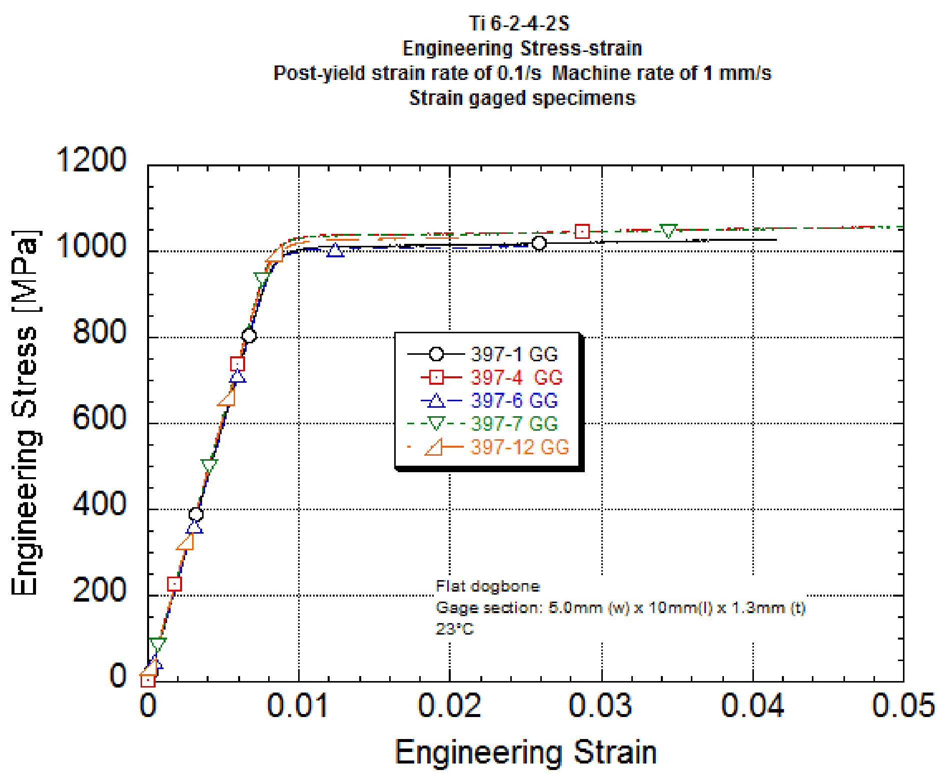

Ti 6-2-4-2S
Engineering Stress-strain
Digital image correlation specimens
Post-yield engineering strain rates
23°C
Engineering Stress [MPa]
Engineering Strain
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
0.1/s
1/s
12/s
150/s

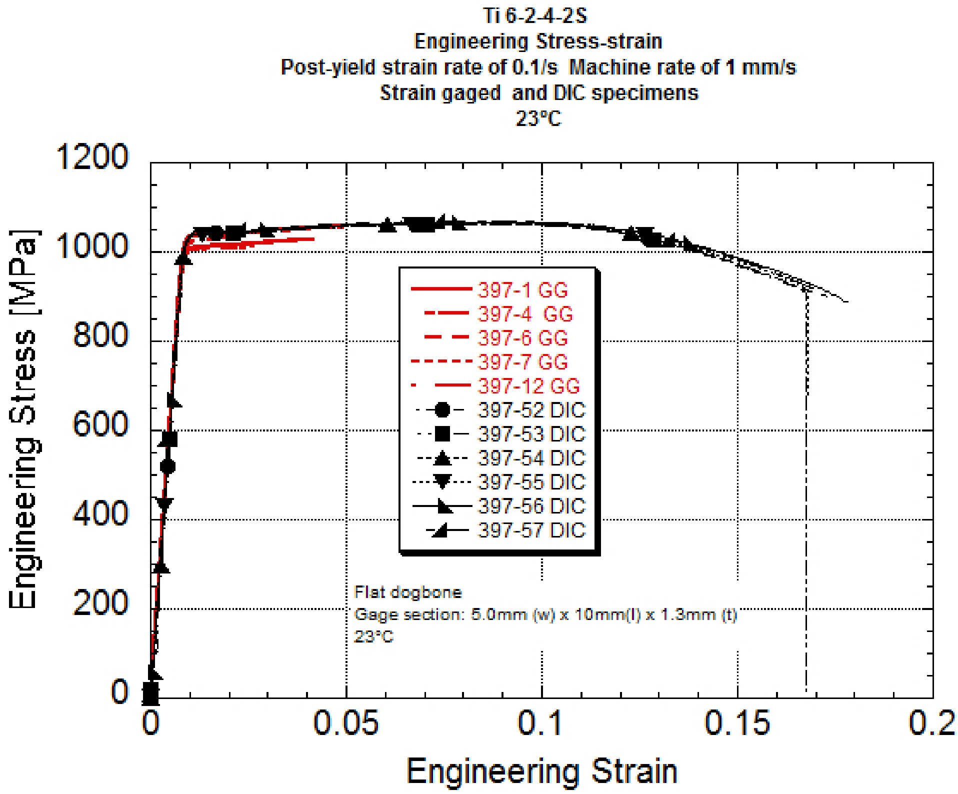

Ti 6-2-4-2S
Engineering Stress-strain
Strain gaged specimens
Post-yield engineering strain rates
23°C
Engineering Stress [MPa]
Engineering Strain
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
0.01/s
1/s
12/s
150/s

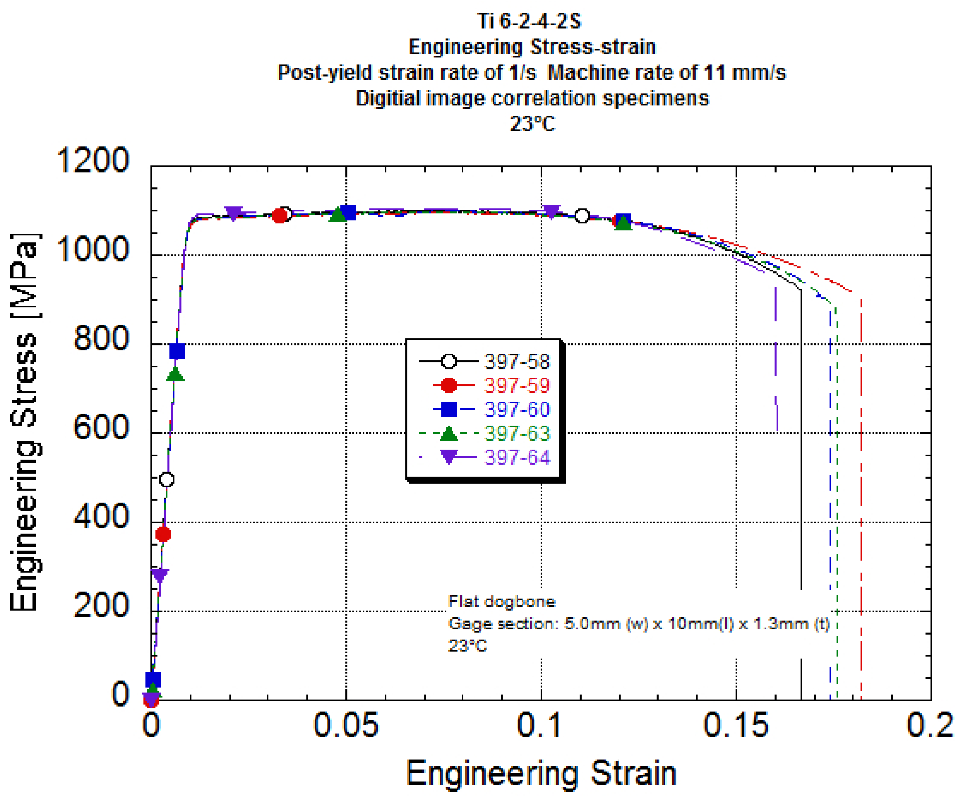


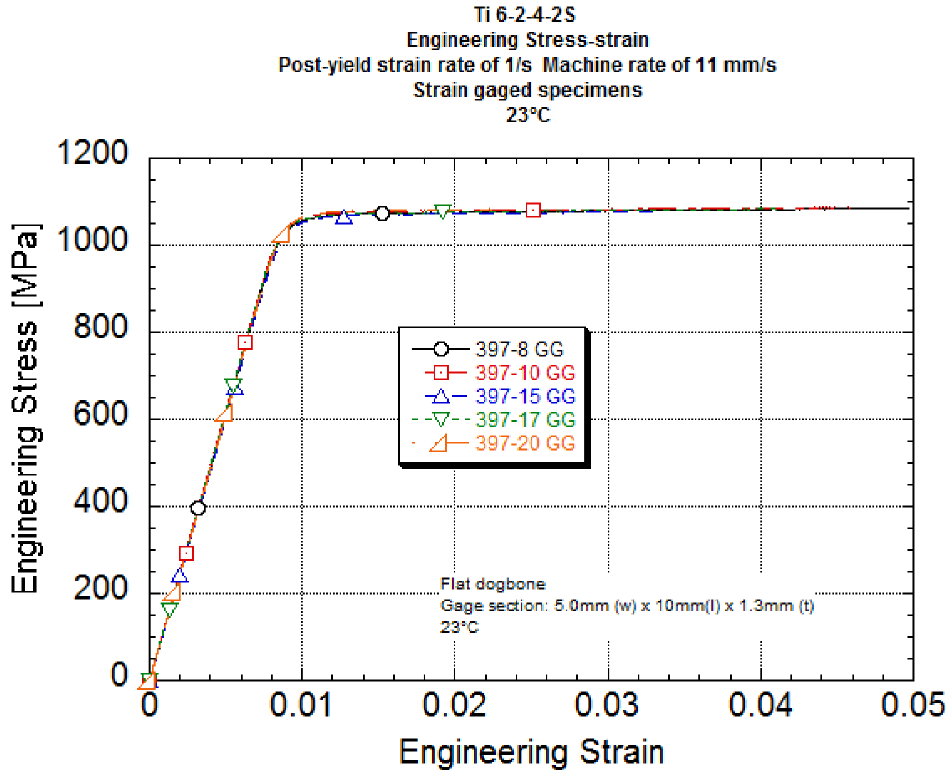
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1 mm/s
Digital image correlation runs
Engineering Stress [MPa]
Engineering Strain
397-52
397-53
397-54
397-55
397-56
397-57
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

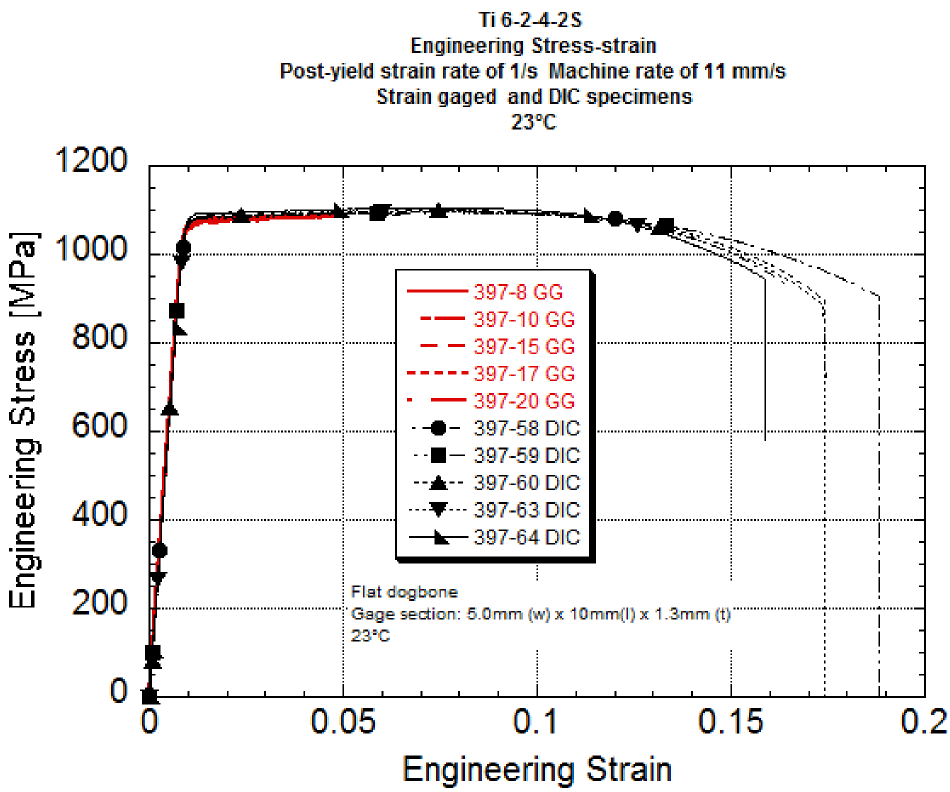


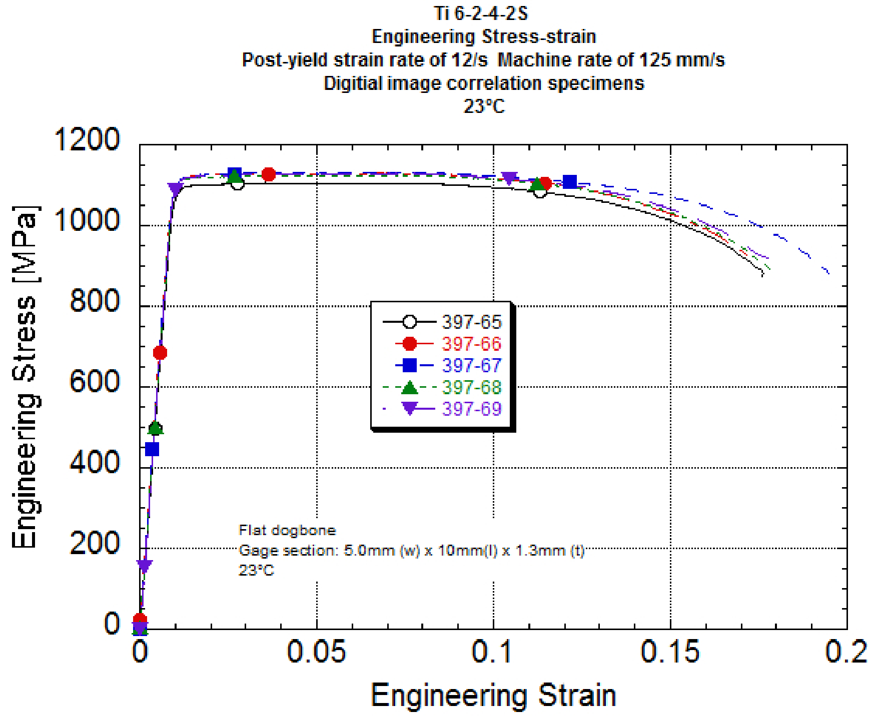
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1 mm/s
Strain gaged specimens
Engineering Stress [MPa]
Engineering Strain
397-1 GG
397-4 GG
397-6 GG
397-7 GG
397-12 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

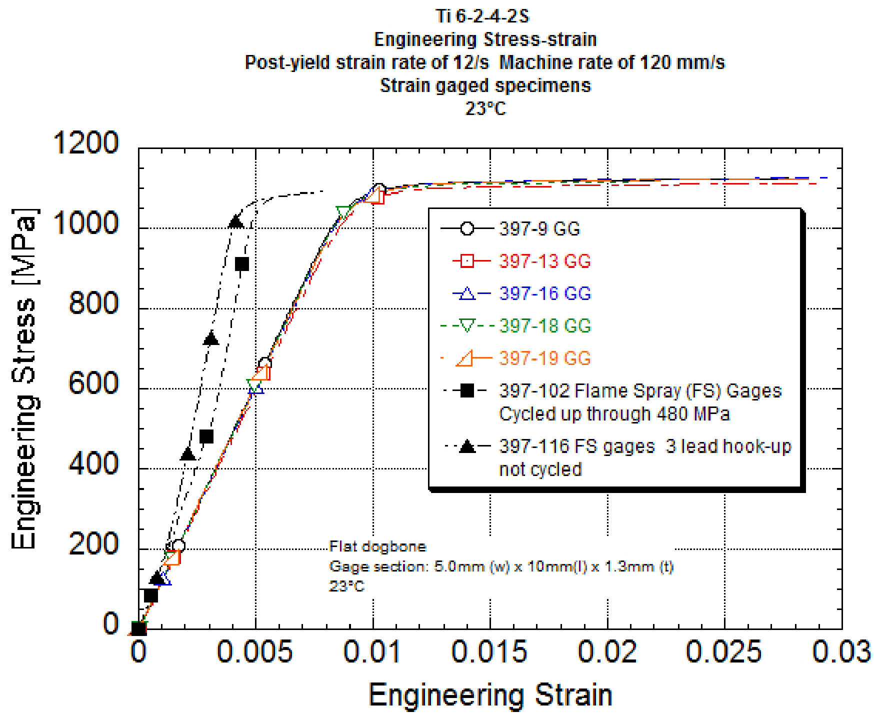

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1 mm/s
Strain gaged and DIC specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-1 GG
397-4 GG
397-6 GG
397-7 GG
397-12 GG
397-52 DIC
397-53 DIC
397-54 DIC
397-55 DIC
397-56 DIC
397-57 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

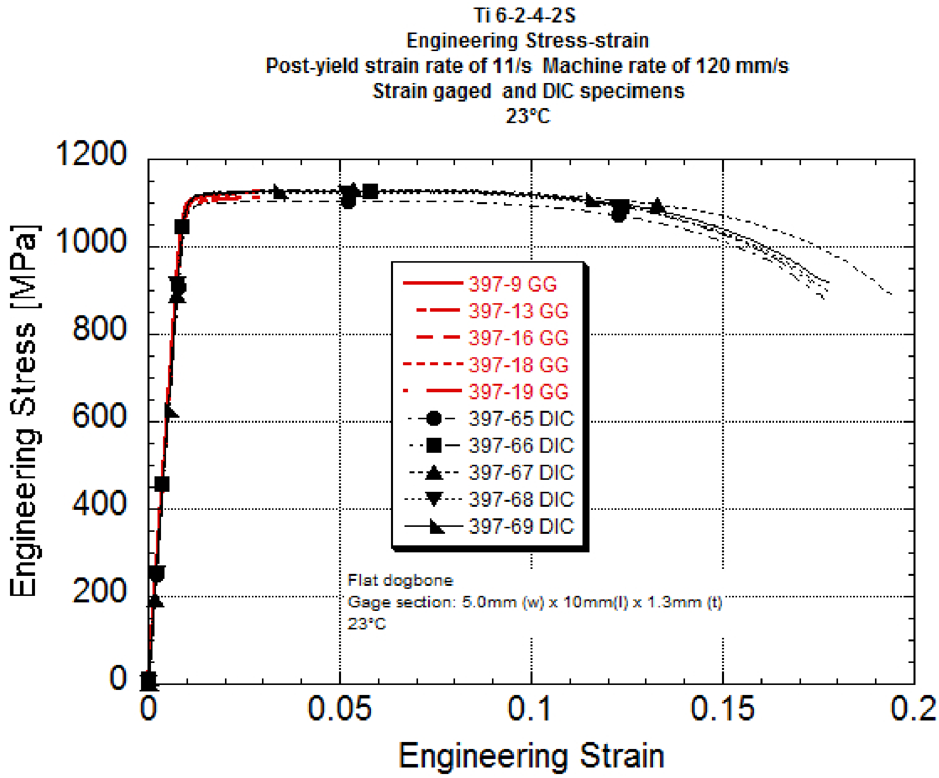

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 11 mm/s
Digitial image correlation specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-58
397-59
397-60
397-63
397-64
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

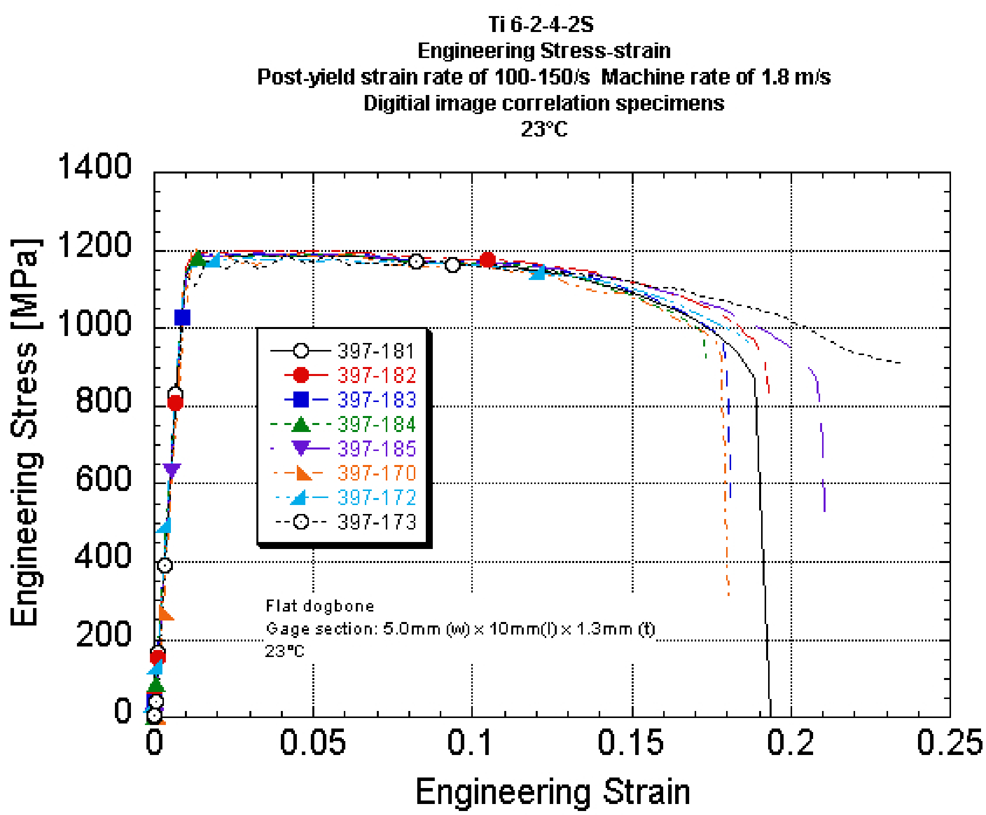

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 11 mm/s
Strain gaged specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-8 GG
397-10 GG
397-15 GG
397-17 GG
397-20 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

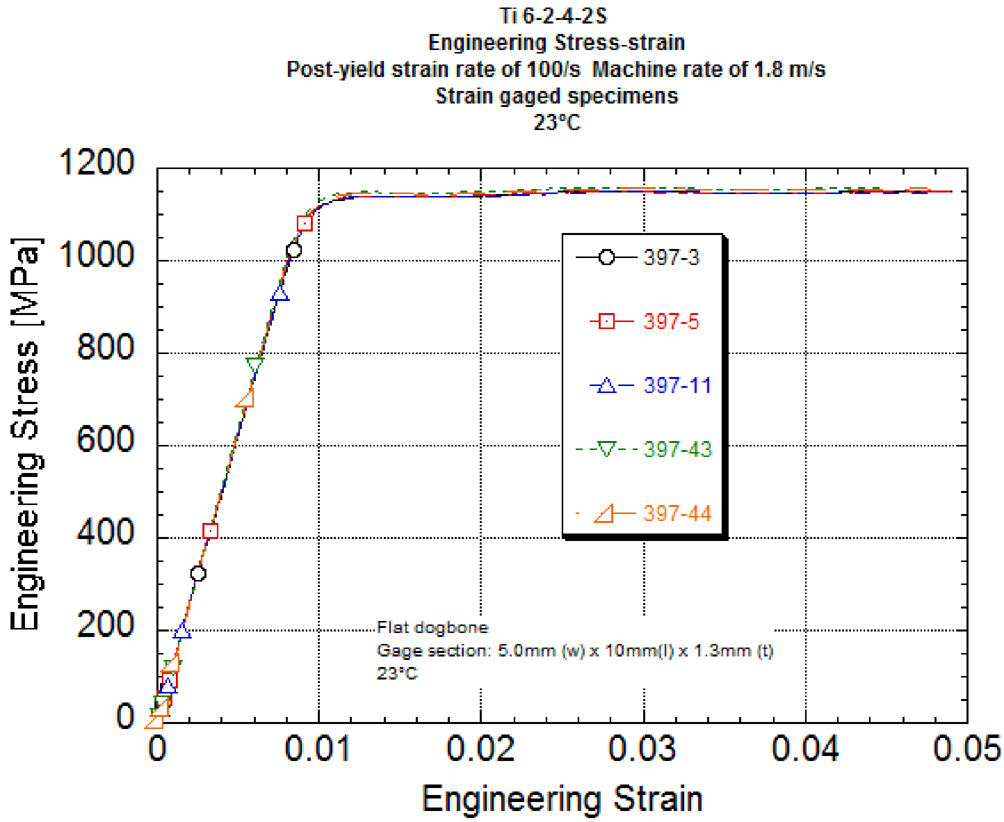

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 11 mm/s
Strain gaged and DIC specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-8 GG
397-10 GG
397-15 GG
397-17 GG
397-20 GG
397-58 DIC
397-59 DIC
397-60 DIC
397-63 DIC
397-64 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 12/s Machine rate of 125 mm/s
Digitial image correlation specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-65
397-66
397-67
397-68
397-69
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

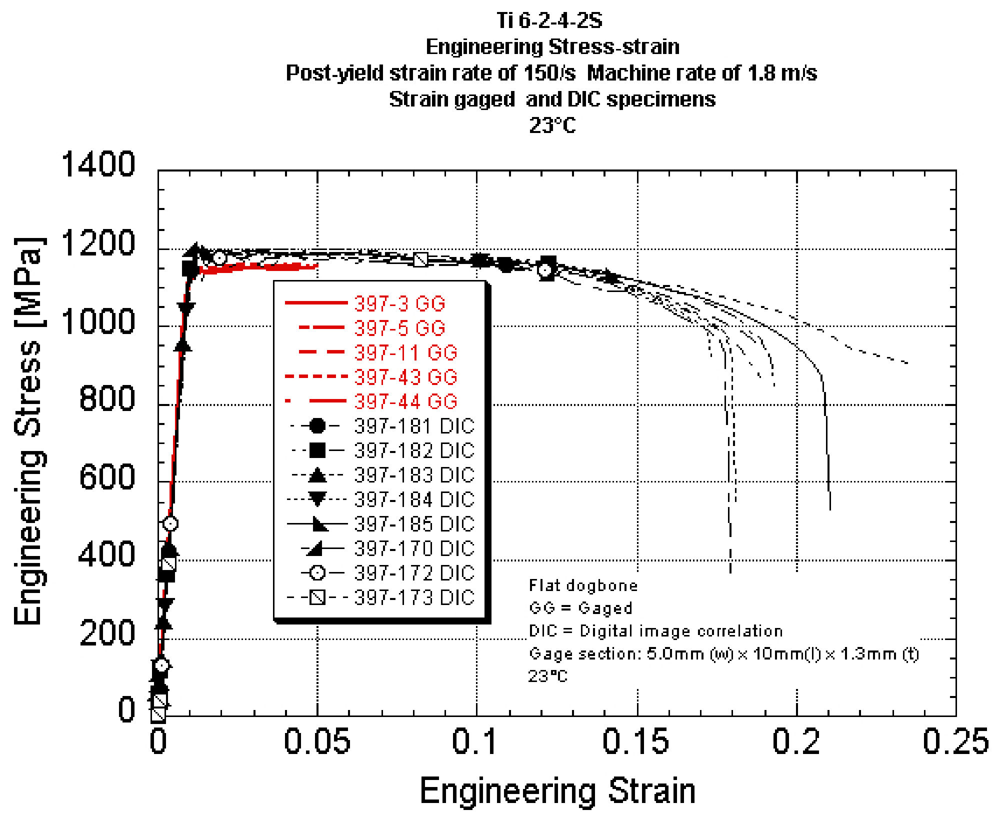

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 12/s Machine rate of 120 mm/s
Strain gaged specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-9 GG
397-13 GG
397-16 GG
397-18 GG
397-19 GG
397-102 Flame Spray (FS) Gages
Cycled up through 480 MPa
397-116 FS gages 3 lead hook-up
not cycled
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 11/s Machine rate of 120 mm/s
Strain gaged and DIC specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-9 GG
397-13 GG
397-16 GG
397-18 GG
397-19 GG
397-65 DIC
397-66 DIC
397-67 DIC
397-68 DIC
397-69 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

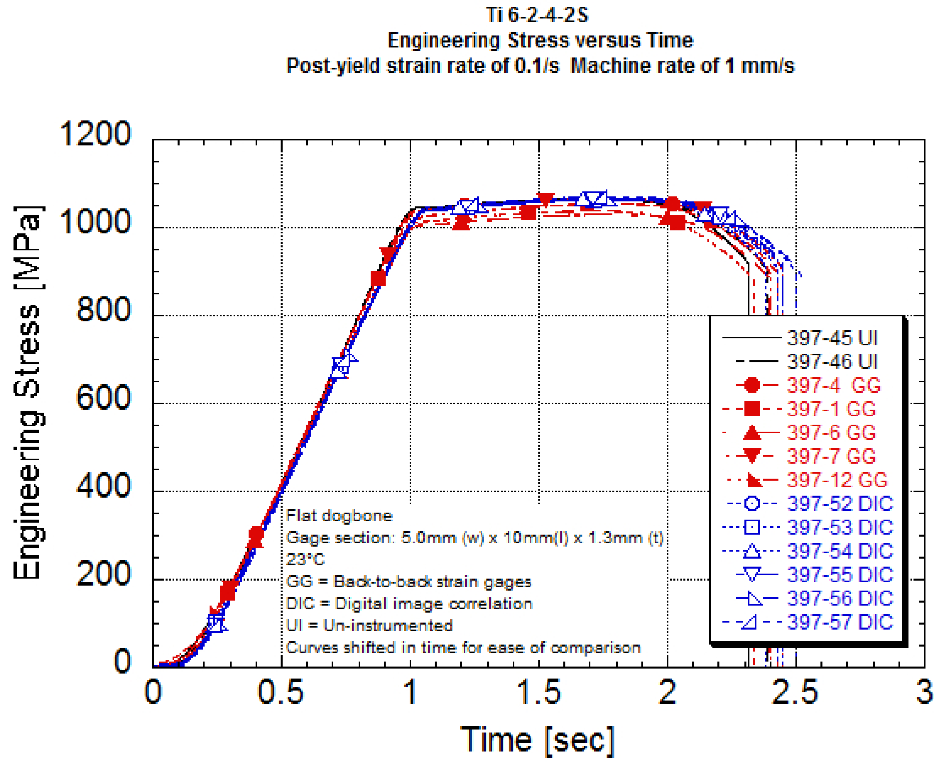

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 100-150/s Machine rate of 1.8 m/s
Digitial image correlation specimens
23°C
Engineering Stress [MPa]
Engineering Strain
397-181
397-182
397-183
397-184
397-185
397-170
397-172
397-173
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

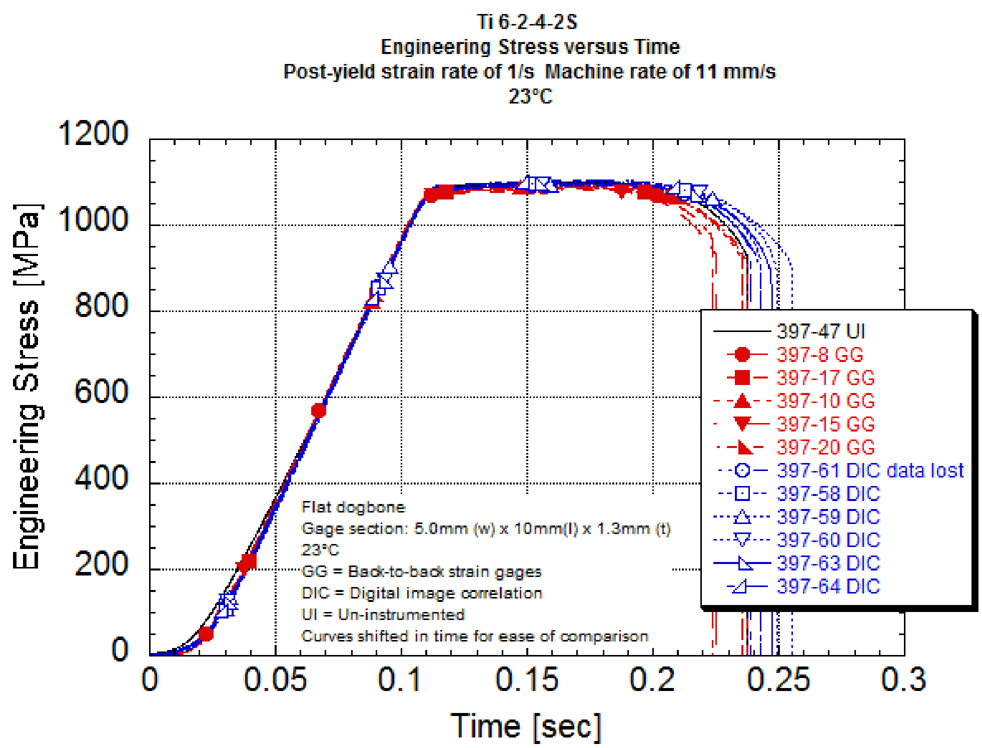


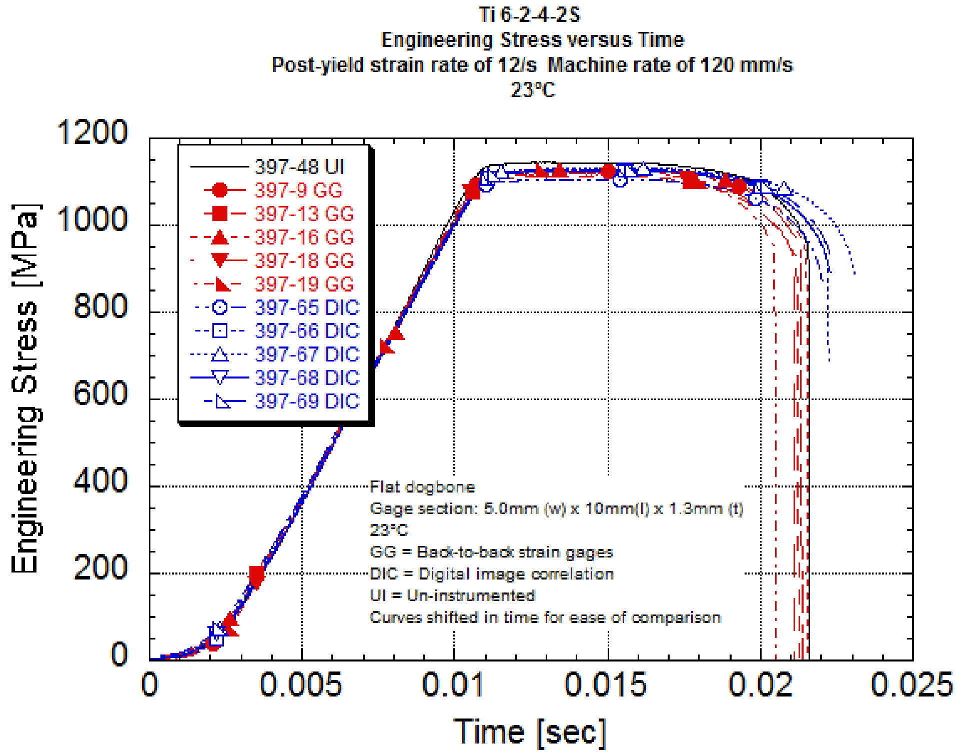
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 100/s Machine rate of 1.8 m/s
Strain gaged specimens
23°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
0
0.01
0.02
0.03
0.04
0.05
397-3
397-5
397-11
397-43
397-44
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C

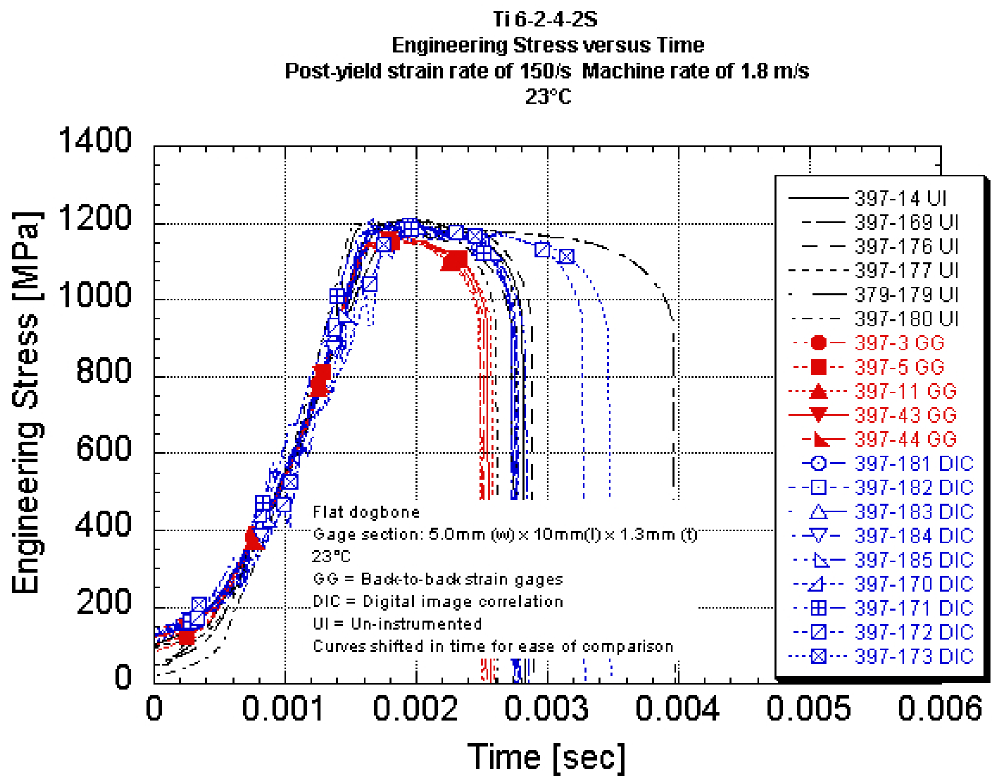


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 150/s Machine rate of 1.8 m/s
Strain gaged and DIC specimens
23°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
1400
0
0.05
0.1
0.15
0.2
0.25
397-3 GG
397-5 GG
397-11 GG
397-43 GG
397-44 GG
397-181 DIC
397-182 DIC
397-183 DIC
397-184 DIC
397-185 DIC
397-170 DIC
397-172 DIC
397-173 DIC
Flat dogbone
GG = Gaged
DIC = Digital image correlation
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 0.1/s Machine rate of 1 mm/s
Engineering Stress [MPa]
Time [sec]
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison
397-45 UI
397-46 UI
397-4 GG
397-1 GG
397-6 GG
397-7 GG
397-12 GG
397-52 DIC
397-53 DIC
397-54 DIC
397-55 DIC
397-56 DIC
397-57 DIC


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 1/s Machine rate of 11 mm/s
23°C
Engineering Stress [MPa]
Time [sec]
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison
397-47 UI
397-8 GG
397-17 GG
397-10 GG
397-15 GG
397-20 GG
397-61 DIC data lost
397-58 DIC
397-59 DIC
397-60 DIC
397-63 DIC
397-64 DIC


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 12/s Machine rate of 120 mm/s
23°C
Engineering Stress [MPa]
Time [sec]
397-48 UI
397-9 GG
397-13 GG
397-16 GG
397-18 GG
397-19 GG
397-65 DIC
397-66 DIC
397-67 DIC
397-68 DIC
397-69 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 150/s Machine rate of 1.8 m/s
23°C
Engineering Stress [MPa]
Time [sec]
397-14 UI
397-169 UI
397-176 UI
397-177 UI
379-179 UI
397-180 UI
397-3 GG
397-5 GG
397-11 GG
397-43 GG
397-44 GG
397-181 DIC
397-182 DIC
397-183 DIC
397-184 DIC
397-185 DIC
397-170 DIC
397-171 DIC
397-172 DIC
397-173 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
23°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison

APPENDIX F: MECH PROPS & SUMMARY GRAPHS – 100°C

Table F1. Mechanical Properties of Ti 6-2-4-2S at 0.1/s and 100°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages and digital image correlation (DIC).

100°C	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 0.1/s	3/1/16	397-21	959	898	0.965	806	-	-	119	1.12	0.112	0.0848	0.0819	2-5	
	3/1/16	397-22	966	907	0.977	783	-	-	118	1.12	0.112	0.0831	0.0803	2-5	
	3/1/16	397-23	968	909	0.977	807	-	-	118	1.12	0.112	0.0815	0.0787	2-5	
	3/1/16	397-24	963	903	0.970	812	-	-	118	1.12	0.112	0.0821	0.0793	2-5	
	3/1/16	397-25	964	904	0.967	815	-	-	119	1.12	0.112	0.0846	0.0818	2-5	
Average			***964***	***904***	***0.971***	***805***			***118***						
Std.Dev.			***3.3***	***4.34***	***0.01***	***12.7***			***0.61***						
Coeff. of Var. [%]			***0.34***	***0.48***	***0.6***	***1.58***			***0.51***						
DIC and Un-instrumented 0.1/s	4/21/16	397-50	979	929	0.985	823	33.9	15.9	115	1.092	0.109	0.0880	0.0842	2-7	
	4/19/16	397-83	982	929	0.986	838	36.0	16.5	119	1.117	0.112	0.0892	0.0853	2-7	
	4/21/16	397-85	982	930	0.986	826	37.9	17.1	119	1.116	0.112	0.0883	0.0844	2-7	
	4/21/16	397-86	988	939	0.992	841	38.8	16.6	119	1.118	0.112	0.0886	0.0847	2-7	
	4/21/16	398-87	983	930	0.987	799	35.8	18.3	117	1.116	0.112	0.0892	0.0853	2-7	
	4/21/16	397-84	981	-	-	816	-	-	-	1.115	0.111	-	-	-	DIC not captured
	3/2/16	397-70	975	-	-	805	-	-	-	1.117	0.112	-	-	-	
Average			***981***	***931***	***0.987***	***821***	***36.5***	***16.9***	***118***						
Std.Dev.			***4.11***	***4.10***	***0.003***	***15.89***	***1.90***	***0.91***	***1.83***						
Coeff. of Var. [%]			***0.42***	***0.44***	***0.29***	***1.94***	***5.22***	***5.39***	***1.56***						
Average [overall]			***974***	***918***	***0.979***	***814***									
Std.Dev.			***9.7***	***14.9***	***0.009***	***16.4***									
Coeff. of Var. [%]			***0.99***	***1.63***	***0.97***	***2.01***									

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table F2. Mechanical Properties of Ti 6-2-4-2S at 1/s and 100°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages and digital image correlation (DIC).

100°C	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]
Gaged 1/s	2/29/16	397-35	984	942	0.997	827	-	-	118	11.18	1.12	0.871	0.841	2-5
	2/29/16	397-36	982	940	1.00	767	-	-	117	11.21	1.12	0.940	0.907	2-5
	3/1/16	397-37	990	944	0.973	815	-	-	120	11.17	1.12	0.890	0.860	2-5
	2/29/16	397-39	982	935	0.990	816	-	-	118	11.19	1.12	0.899	0.903	2-5
	2/29/16	397-40	985	939	0.995	795	-	-	118	11.20	1.12	0.935	0.860	2-5
Average			***984***	***940***	***0.992***	***804***			***118***					
Std.Dev.			***3.2***	***3.59***	***0.01***	***23.7***			***0.96***					
Coeff. of Var. [%]			***0.33***	***0.38***	***1.2***	***2.95***			***0.81***					
DIC and Un-instrumented 1/s	4/22/16	397-88	996	964	1.02	829	41.0	16.3	-	11.3	1.13	0.971	0.923	2-8
	4/22/16	397-89	1,009	971	1.02	818	37.2	18.5	-	11.2	1.12	0.948	0.902	2-8
	4/22/16	397-90	992	954	1.01	827	40.2	16.9	-	11.2	1.12	0.927	0.882	2-8
	4/22/16	397-91	1,010	973	1.02	826	40.4	17.2	-	11.2	1.12	0.934	0.889	2-8
	4/22/16	397-92	1,006	969	1.02	851	33.7	16.5	-	11.2	1.12	0.946	0.900	2-8
	3/2/16	397-71	1,000	-	-	810	-	-	-	11.2	1.12	-	-	-
Average			***1,002***	***966***	***1.02***	***827***	***38.5***	***17.1***						
Std.Dev.			***7.24***	***7.81***	***0.01***	***13.81***	***3.07***	***0.87***						
Coeff. of Var. [%]			***0.72***	***0.81***	***0.60***	***1.67***	***7.97***	***5.07***						
Average [overall]			***994***	***953***	***1.00***	***816***								
Std.Dev.			***10.8***	***15.0***	***0.02***	***21.5***								
Coeff. of Var. [%]			***1.09***	***1.57***	***1.61***	***2.64***								

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table F3. Mechanical Properties of Ti 6-2-4-2S at 10/s and 100°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness

Strain measured with gages and digital image correlation (DIC).

100°C	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]
Gaged 10/s	2/26/16	397-26	1,027	992	1.03	863	-	-	119	127	12.7	11.6	11.2	2-5
	2/26/16	397-27	1,028	992	1.04	872	-	-	119	119	11.9	11.2	10.8	2-5
	2/26/16	397-28	1,025	985	1.03	808	-	-	119	125	12.5	10.6	10.2	2-5
	2/26/16	397-29	1,020	990	1.04	841	-	-	118	125	12.5	11.4	11.0	2-5
	2/26/16	397-30	1,025	991	1.05	836	-	-	118	125	12.5	11.4	11.0	2-5
	2/29/16	397-31	1,024	991	1.04	850	-	-	117	127	12.7	11.2	10.9	2-4.5
	4/26/16	397-33	1,018	977	1.04	846	-	-	117	125	12.5	14.1	13.6	2-5
Average			***1,024***	***988***	***1.04***	***845***			***118***					
Std.Dev.			***3.6***	***5.42***	***0.01***	***20.7***			***0.86***					
Coeff. of Var. [%]			***0.35***	***0.55***	***0.6***	***2.45***			***0.73***					
DIC and Un-instrumented 10/s	4/25/16	397-93	1,043	1,012	1.06	855	38.7	18.4	118	125	12.5	12.0	11.5	2-7
	4/25/16	397-94	1,042	1,012	1.06	885	36.4	17.5	119	125	12.5	12.0	11.4	2-7
	4/25/16	397-95	1,032	1,001	1.05	862	37.5	17.0	115	125	12.5	12.1	11.6	2-7
	4/25/16	397-96	1,038	1,010	1.06	860	40.0	16.2	120	125	12.5	12.0	11.4	2-7
	4/25/16	397-97	1,043	1,018	1.06	860	42.2	17.3	118	125	12.5	12.2	11.6	2-7
	2/25/16	397-151	1,036	-	-	832	-	-	-	127	12.7	-	-	-
Average			***1,039***	***1,011***	***1.06***	***859***		***17.3***	***118***					
Std.Dev.			***4.56***	***6.15***	***0.005***	***17.00***		***0.80***	***1.86***					
Coeff. of Var. [%]			***0.44***	***0.61***	***0.5***	***1.98***		***4.64***	***1.58***					
Average [overall]			***1,031***	***998***	***1.05***	***852***								
Std.Dev.			***8.7***	***12.7***	***0.010***	***19.7***								
Coeff. of Var. [%]			***0.85***	***1.28***	***0.99***	***2.31***								

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

Table F4. Mechanical Properties of Ti 6-2-4-2S at 150/s and 100°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages and digital image correlation (DIC).

100°C	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Failure Strain at Break (Local strain) [%]	Failure Strain at Break (Global strain) [%]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
Gaged 150/s	7/5/16	397-32	1,088	1,064	1.06	886	-	-	124	1882	188	160	154	3-4.9	
	7/5/16	397-34	1,082	1,061	1.07	855	-	-	122	1895	189	170	163	3-4.9	
	7/5/16	397-41	1,085	1,064	1.06	862	-	-	123	1895	189	147	142	3-4.7	
	7/6/16	397-153	1,104	1,097	1.05	863	-	-	129	1887	189	-	-	-	
	7/6/16	397-159	1,099	1,091	1.04	903	-	-	129	1889	189	-	-	-	
Average			***1,091***	***1,076***	***1.06***	***874***			***125***						
Std.Dev.			***9.3***	***17.22***	***0.01***	***19.8***			***3.4***						
Coeff. of Var. [%]			***0.85***	***1.60***	***1.1***	***2.27***			***2.7***						
DIC and Un-instrumented 150/s	6/29/16	397-186	1,103	1,019	1.06	871	41.7	18.0	118	1898	190	153	145	2.2-6.4	
	6/29/16	397-187	1,084	1,058	1.04	888	42.0	16.7	113	1918	192	160	151	2.2-6.4	
	6/30/16	397-188	1,098	-	-	904	-	-	-	1891	189	149	-	-	
	6/30/16	397-189	1,088	-	-	892	-	-	-	1898	190	148	-	-	DIC data not captured
	6/30/16	397-190	1,105	1,087	1.07	895	48.4	15.1	118	1905	190	149	140	2.2-6.4	DIC data not captured
	7/1/16	397-191	1,096	1,079	1.06	898	39.9	15.8	116	1878	188	148	140	2.2-6.4	
	7/1/16	397-192	1,105	1,085	1.07	909	33.6	15.7	119	1903	190	147	139	2.2-6.4	
	6/29/16	397-178	1,111	-	-	894	-	-	-	1888	189	-	-	-	
Average			***1,099***	***1,066***	***1.06***	***894***	***41.1***	***16.3***	***117***						
Std.Dev.			***9.23***	***28.52***	***0.009***	***11.31***	***5.31***	***1.14***	***2.41***						
Coeff. of Var. [%]			***0.84***	***2.68***	***0.9***	***1.27***	***12.92***	***6.98***	***2.07***						
Average overall [150/s]			***1,096***	***1,071***	***1.06***	***886***			***121***						
Std.Dev.			***9.61***	***22.82***	***0.01***	***17.60***			***5.43***						
Coeff. of Var. [%]			***0.88***	***2.13***	***0.95***	***1.99***			***4.49***						

Average gaged specimen modulus used to determine yield data for all specimens tested at the same rate.

*Measured rate using either the strain gage data or global DIC strain. Rate determined over a strain range after yield and up to UTS.

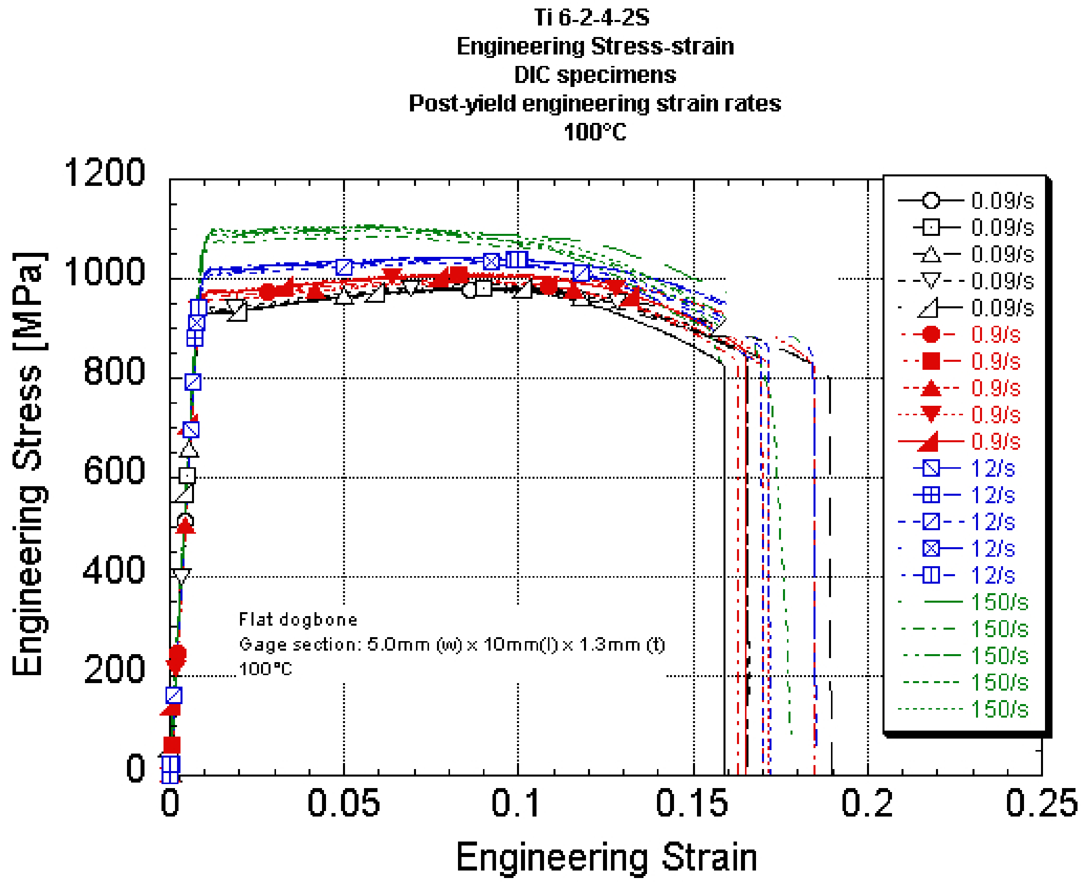
Table F5. Reduction in Area Measurements of Ti 6-2-4-2S at 100°C

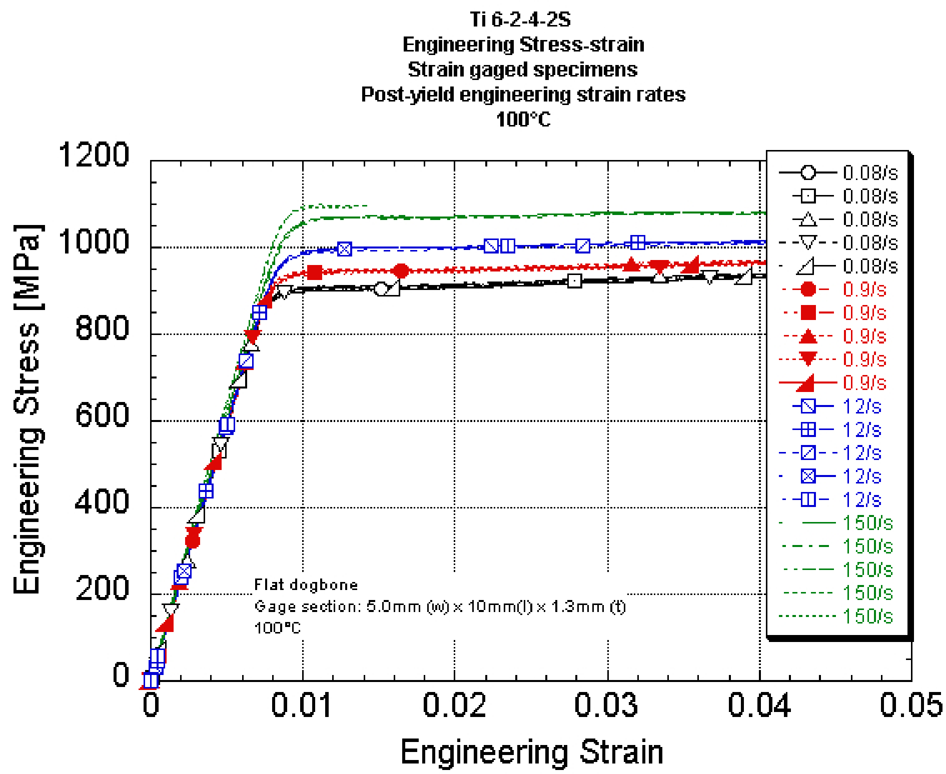
Test Temperature [°C]	Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Measured Strain(2) to Failure [%]	Reduction in Area [%]
100	0.1	397-21	-	-	28.9
		397-22	-	-	35.4
		397-23	-	-	33.2
		397-24	-	-	30.5
		397-25	-	-	27.5
		397-50	-	-	31.8
		397-70	-	-	28.3
		397-83	-	16.5	33.2
		397-84	-	-	33.1
		397-85	-	17.1	31.8
		397-86	-	16.6	31.3
		397-87	-	18.3	33.2
		Average		***17.1***	***31.5***
		Standard Deviation		***0.8***	***2.3***
		Coeff of Variation [%]		***4.8***	***7.4***
100	1	397-35	-	-	34.0
		397-36	-	-	32.2
		397-37	-	-	32.4
		397-39	-	-	31.7
		397-40	-	-	30.0
		397-71	17.1	-	30.6
		397-88	-	16.3	32.1
		397-89	-	18.5	31.1
		397-90	-	16.9	31.5
		397-91	-	17.2	32.7
		397-92	-	16.5	33.0
		397-100	15.4	-	29.5
		Average	***16.2***	***17.1***	***31.7***
		Standard Deviation		***0.9***	***1.3***
		Coeff of Variation [%]		***5.1***	***4.0***

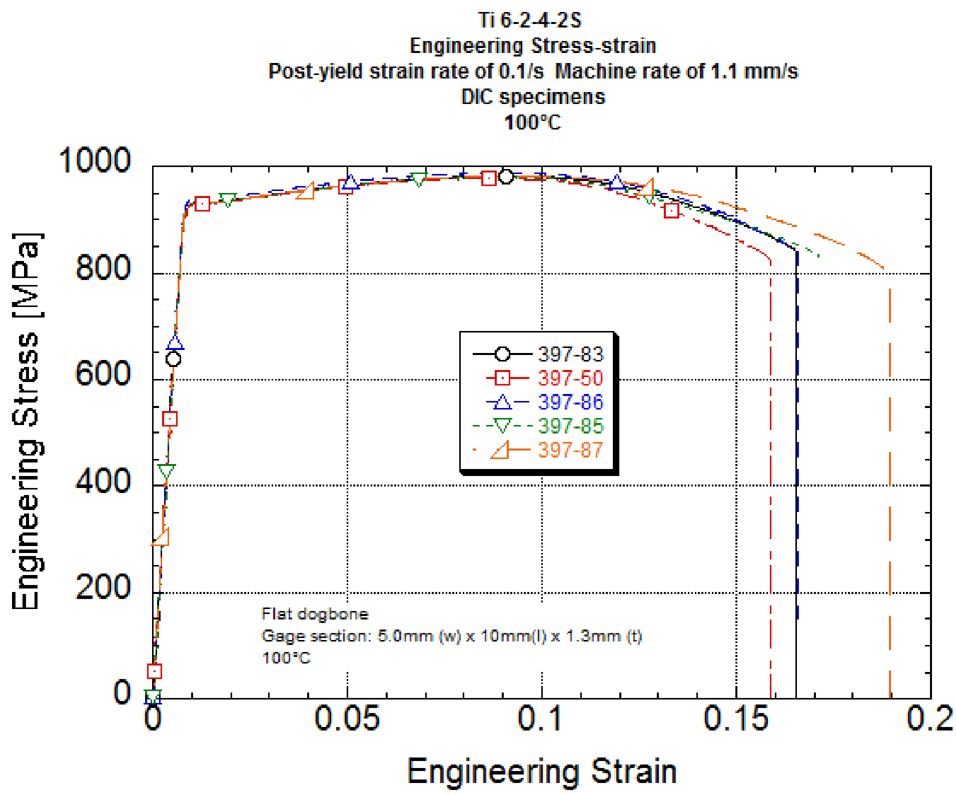
Note 1 Average measured strain rate.
Note 2 Using digital image correlation

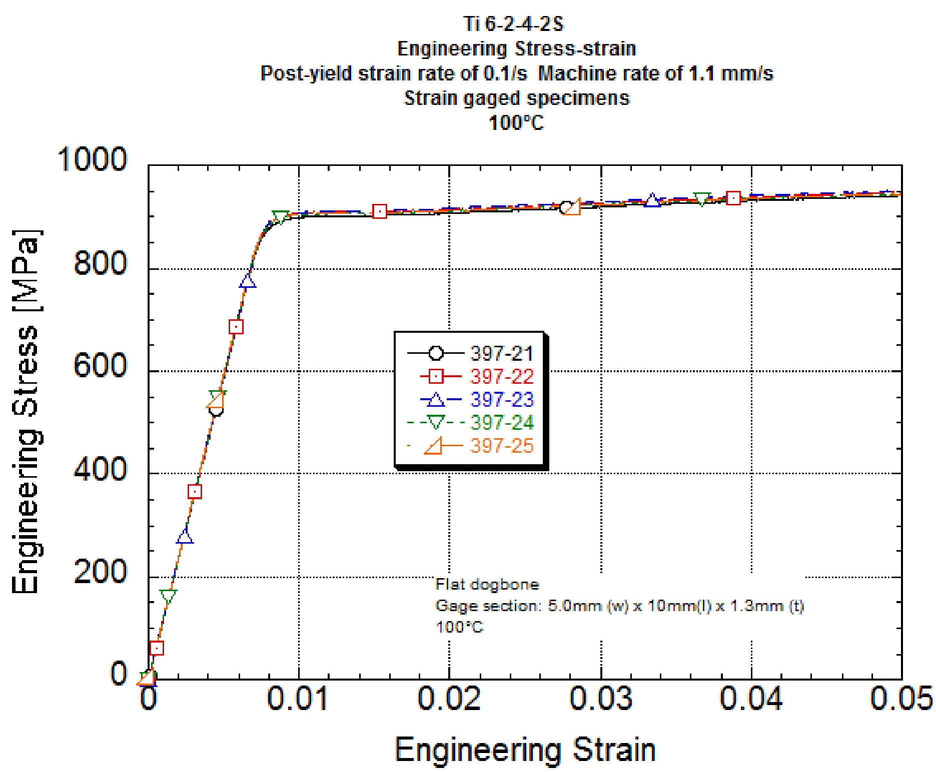
Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Measured Strain(2) to Failure [%]	Reduction in Area [%]
12	397-26	-	-	31.8
	397-27	-	-	28.0
	397-28	-	-	30.4
	397-29	-	-	33.7
	397-30	-	-	33.0
	397-31	-	-	33.5
	397-33	-	-	29.5
	397-93	-	18.4	33.0
	397-94	-	17.5	33.8
	397-95	-	17.0	28.9
	397-96	-	16.2	32.6
	397-97	-	17.3	31.2
	397-151	-	-	41.9
	Average		***17.3***	***32.4***
	Standard Deviation		***0.8***	***3.4***
	Coeff of Variation [%]		***4.6***	***10.6***
150	397-32	-	-	31.4
	397-34	-	-	34.2
	397-41	-	-	31.7
	397-153	-	-	29.5
	397-159	-	-	30.1
	397-178	14.2	-	33.1
	397-186	17.6	18.0	34.0
	397-187	18.2	16.7	34.5
	397-188	14.2		34.7
	397-189	14.3		30.8
	397-190	15.7	15.1	28.6
	397-191	14.4	15.8	31.4
	397-192	16.2	15.7	30.9
	Average	***15.6***	***16.3***	***31.9***
	Standard Deviation	***1.6***	***1.1***	***2.0***
	Coeff of Variation [%]	***10.3***	***7.0***	***6.3***

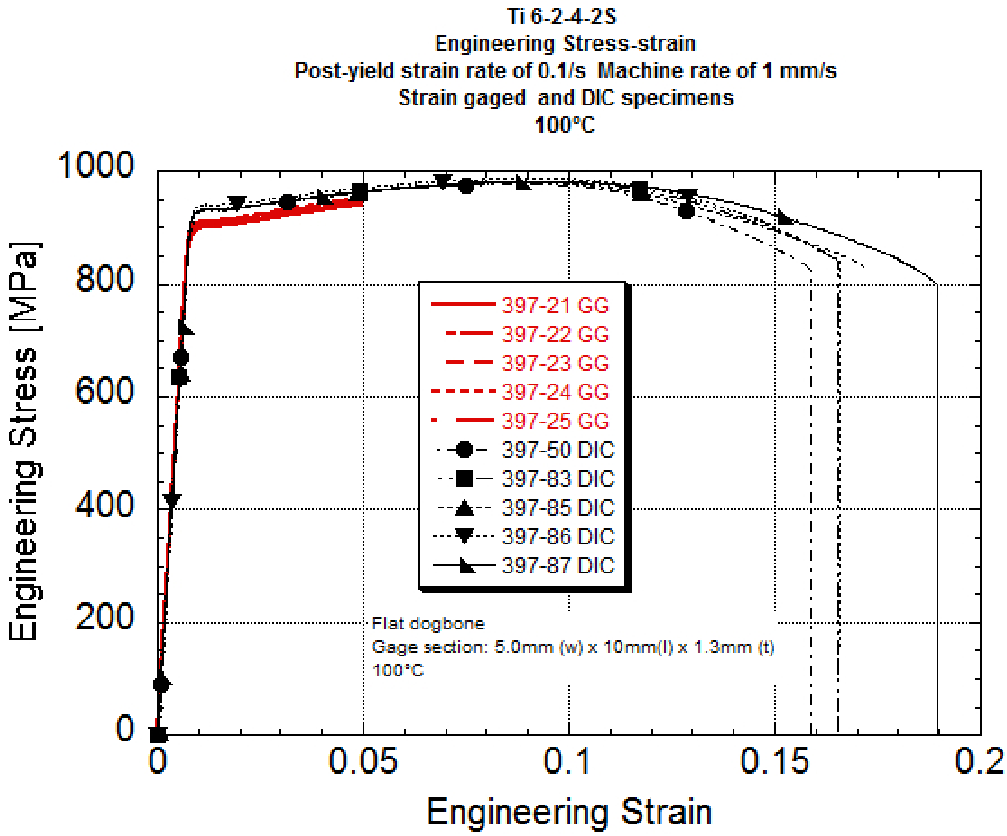
Note 1 Average measured strain rate.
Note 2 Using digital image correlation

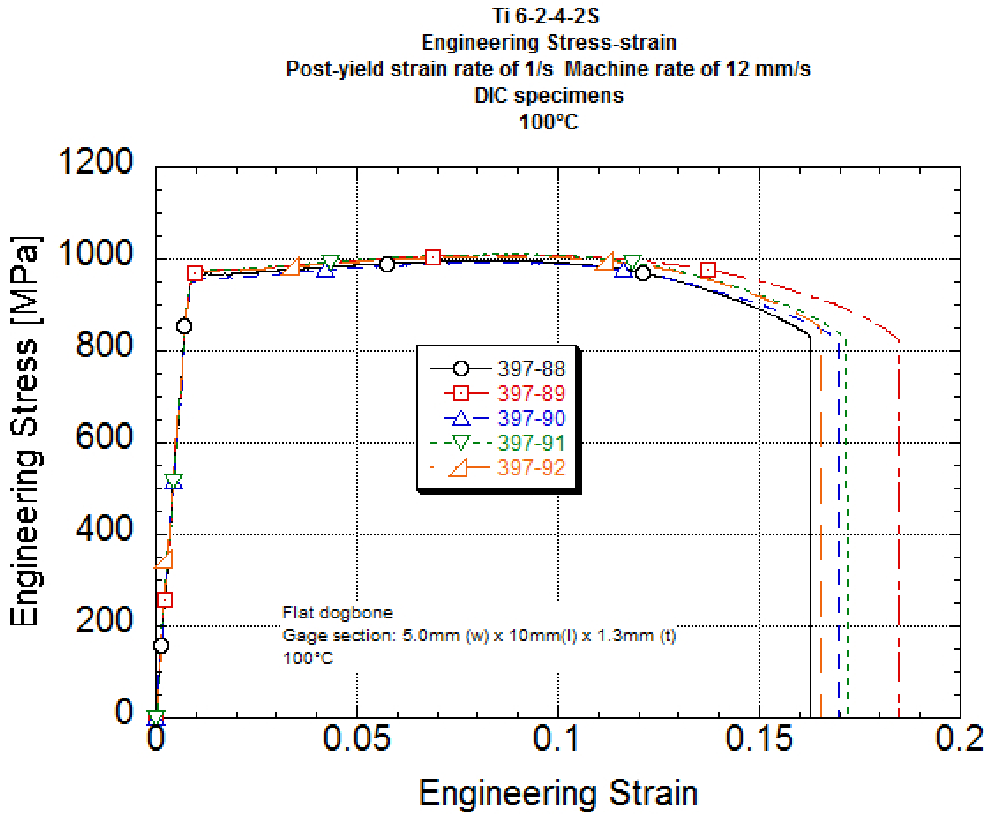

Ti 6-2-4-2S
Engineering Stress-strain
DIC specimens
Post-yield engineering strain rates
100°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
0
0.05
0.1
0.15
0.2
0.25
0.09/s
0.09/s
0.09/s
0.09/s
0.09/s
0.9/s
0.9/s
0.9/s
0.9/s
0.9/s
12/s
12/s
12/s
12/s
12/s
150/s
150/s
150/s
150/s
150/s
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

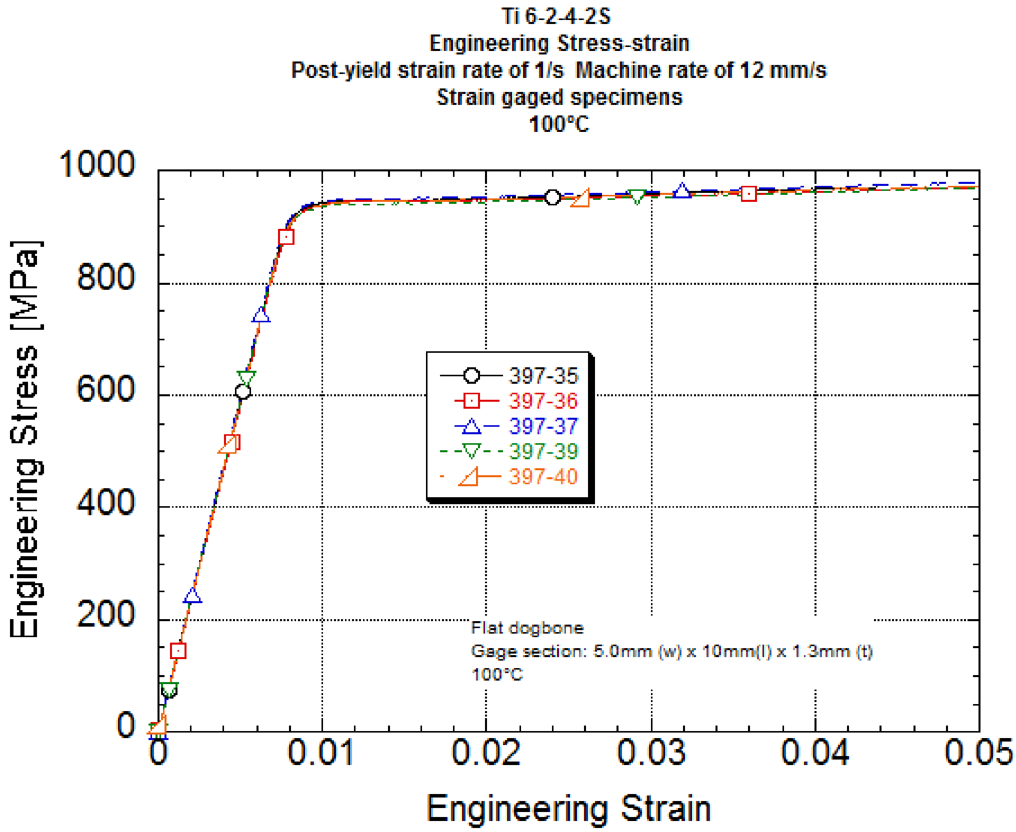

Ti 6-2-4-2S
Engineering Stress-strain
Strain gaged specimens
Post-yield engineering strain rates
100°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
0
0.01
0.02
0.03
0.04
0.05
0.08/s
0.08/s
0.08/s
0.08/s
0.08/s
0.9/s
0.9/s
0.9/s
0.9/s
0.9/s
12/s
12/s
12/s
12/s
12/s
150/s
150/s
150/s
150/s
150/s
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

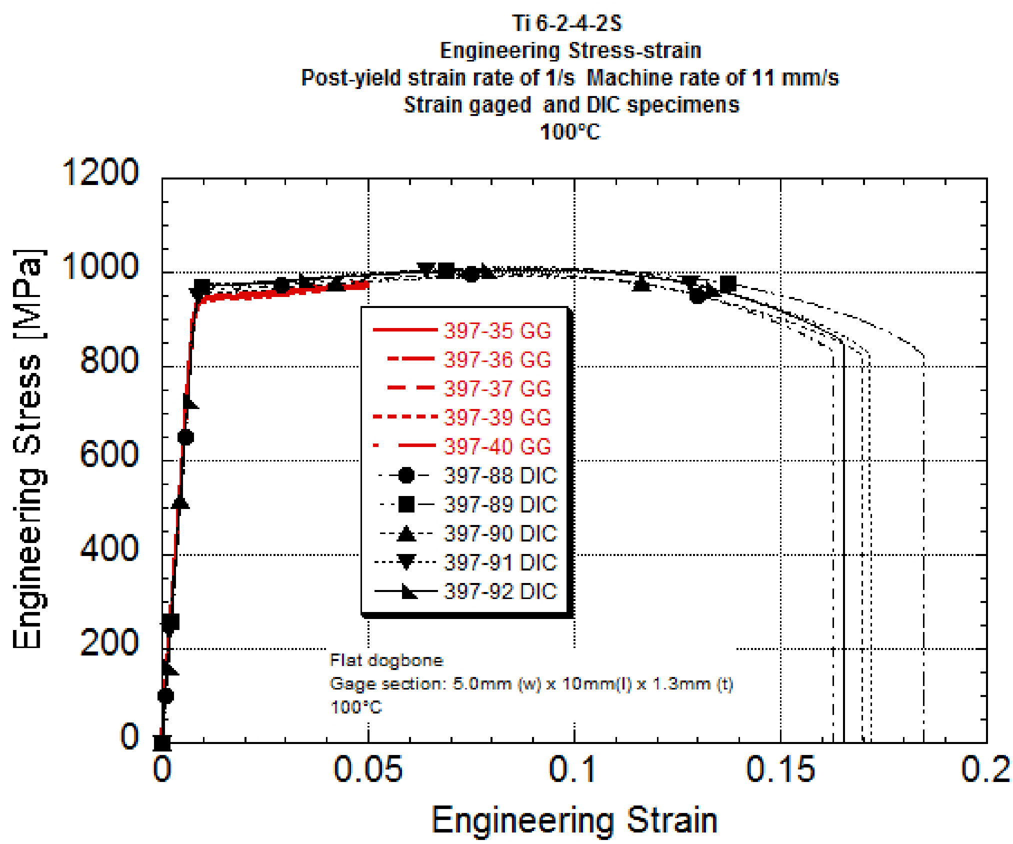

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1.1 mm/s
DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-83
397-50
397-86
397-85
397-87
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

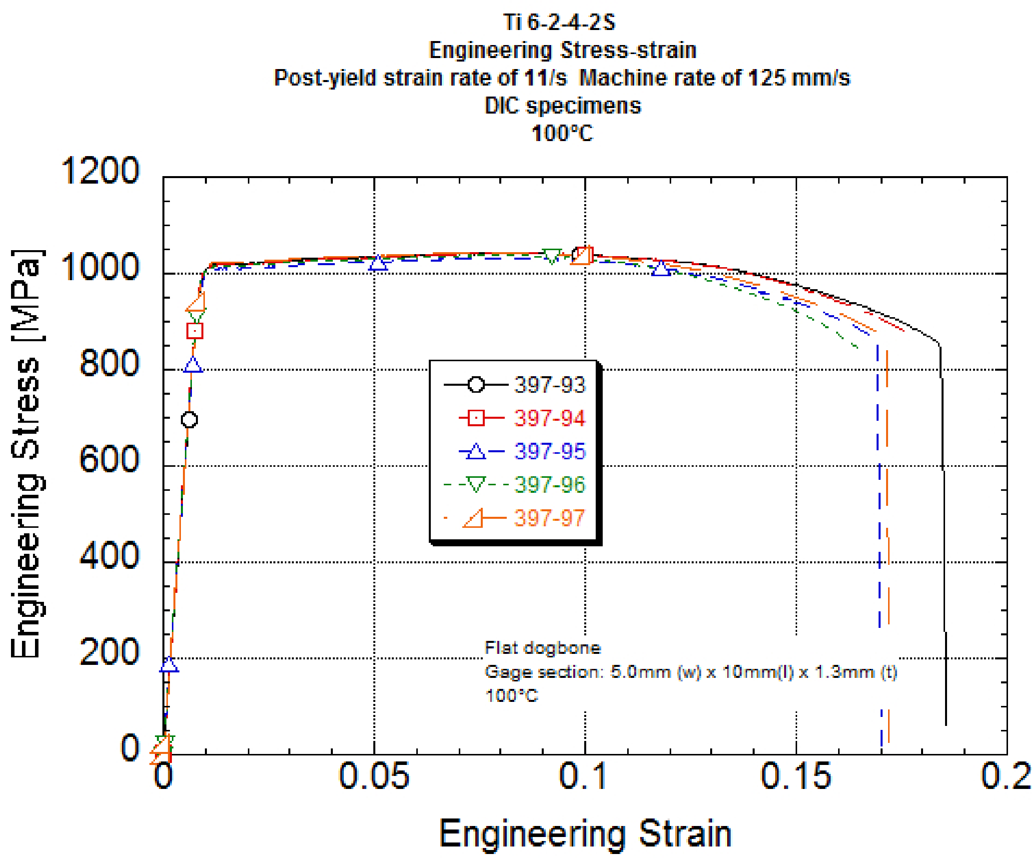

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1.1 mm/s
Strain gaged specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-21
397-22
397-23
397-24
397-25
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 0.1/s Machine rate of 1 mm/s
Strain gaged and DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
397-21 GG
397-22 GG
397-23 GG
397-24 GG
397-25 GG
397-50 DIC
397-83 DIC
397-85 DIC
397-86 DIC
397-87 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

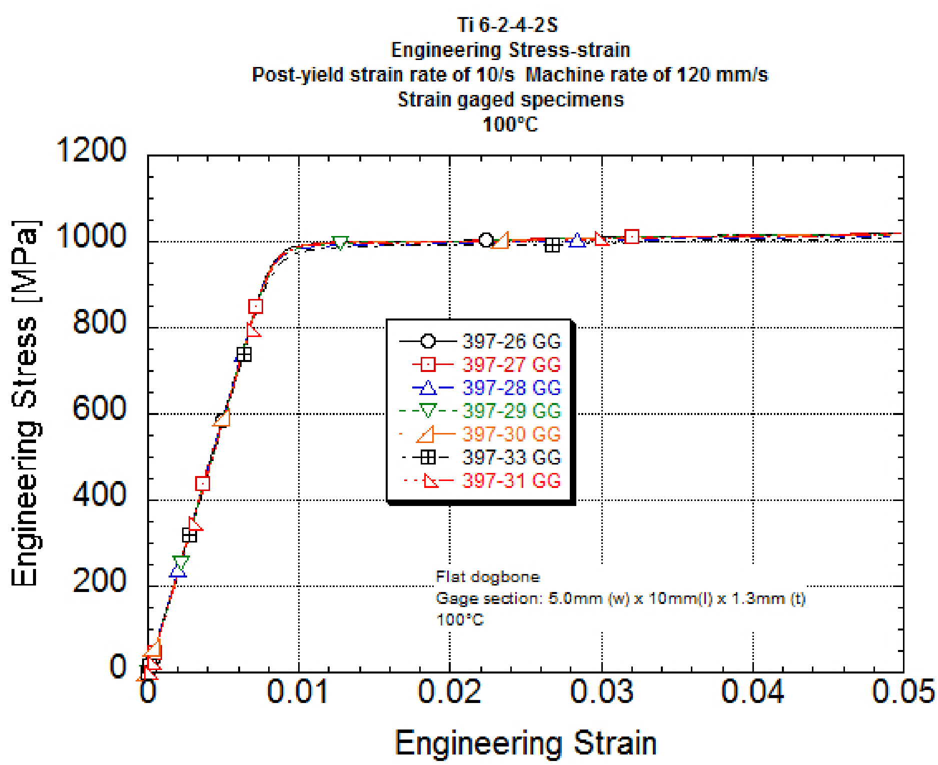

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 12 mm/s
DIC specimens
100°C
Engineering Stress [MPa]
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
Engineering Strain
397-88
397-89
397-90
397-91
397-92
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 12 mm/s
Strain gaged specimens
100°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
0
0.01
0.02
0.03
0.04
0.05
397-35
397-36
397-37
397-39
397-40
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

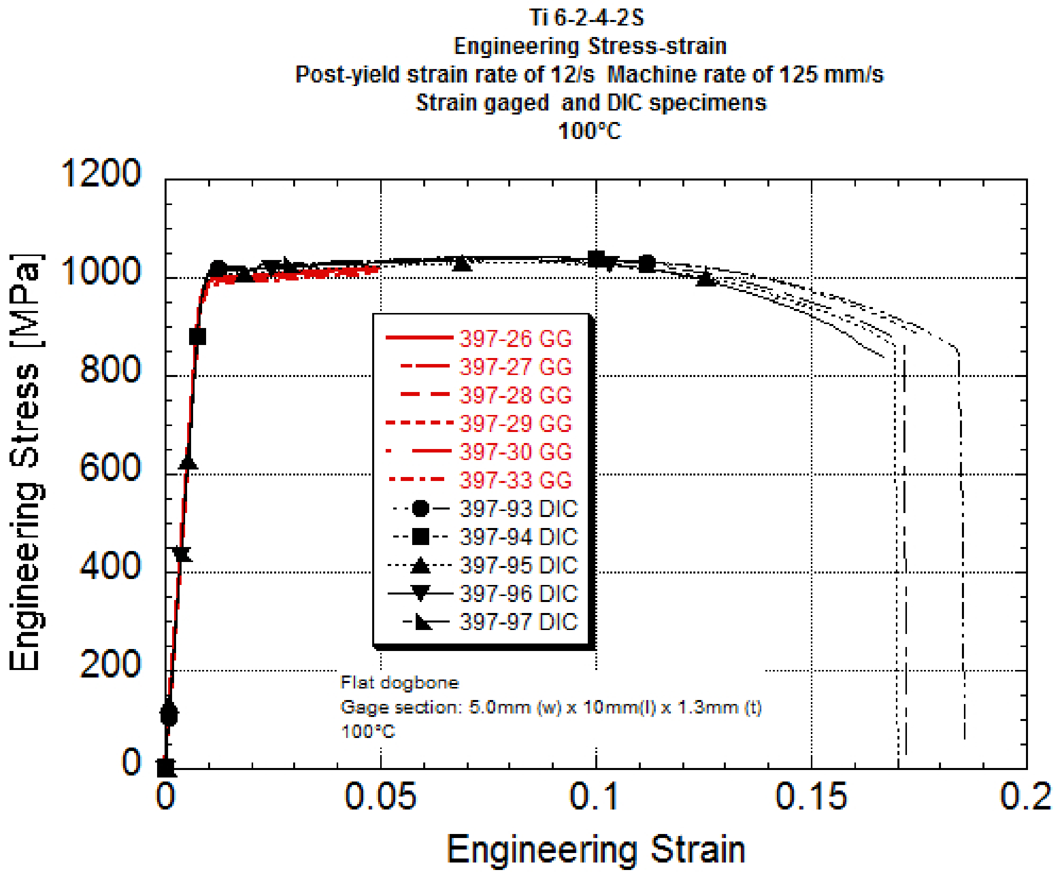

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 1/s Machine rate of 11 mm/s
Strain gaged and DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
0
0.05
0.1
0.15
0.2
397-35 GG
397-36 GG
397-37 GG
397-39 GG
397-40 GG
397-88 DIC
397-89 DIC
397-90 DIC
397-91 DIC
397-92 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C



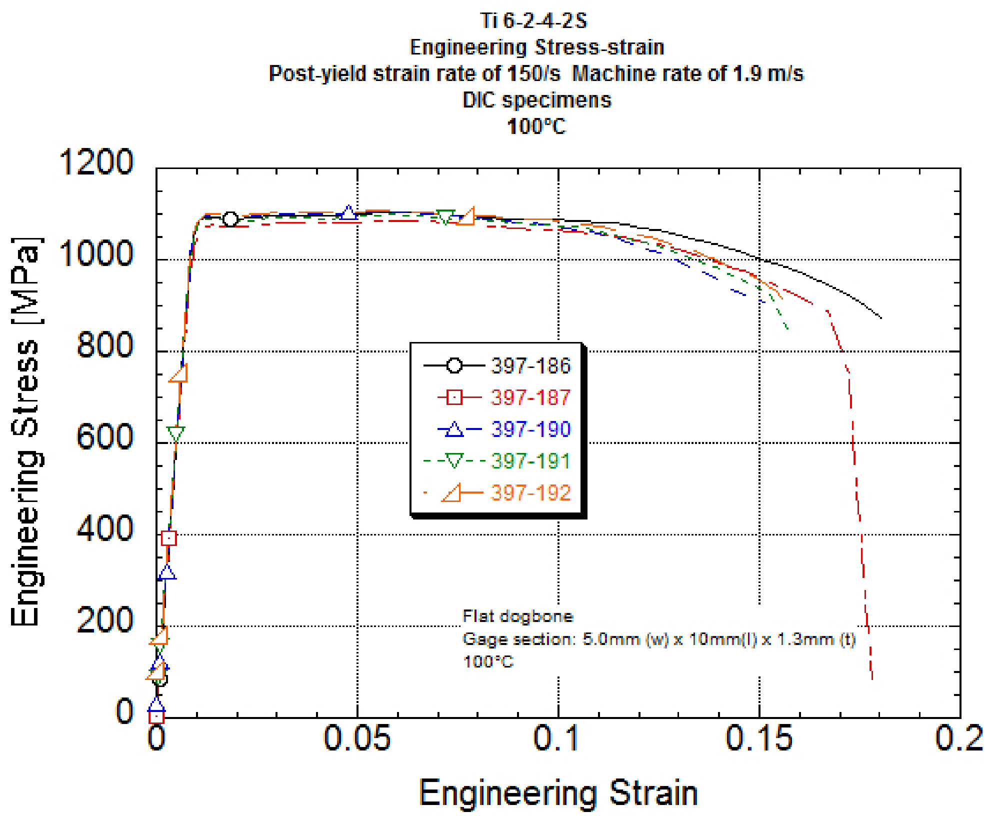
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 11/s Machine rate of 125 mm/s
DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-93
397-94
397-95
397-96
397-97
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C



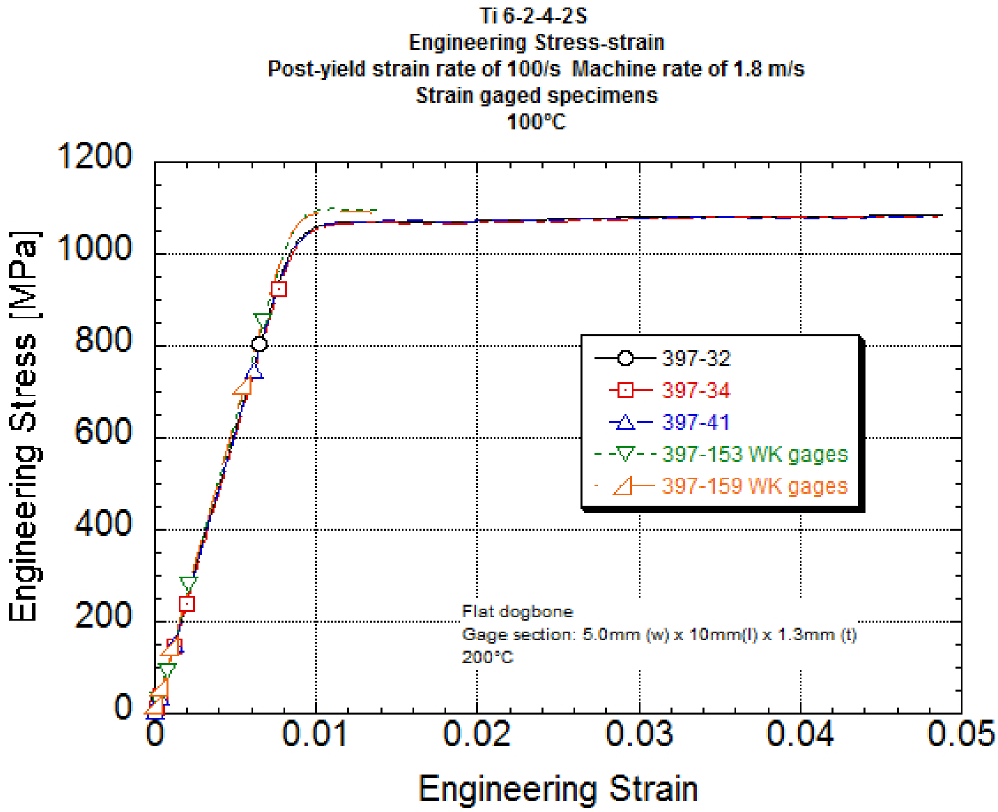
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 10/s Machine rate of 120 mm/s
Strain gaged specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-26 GG
397-27 GG
397-28 GG
397-29 GG
397-30 GG
397-33 GG
397-31 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

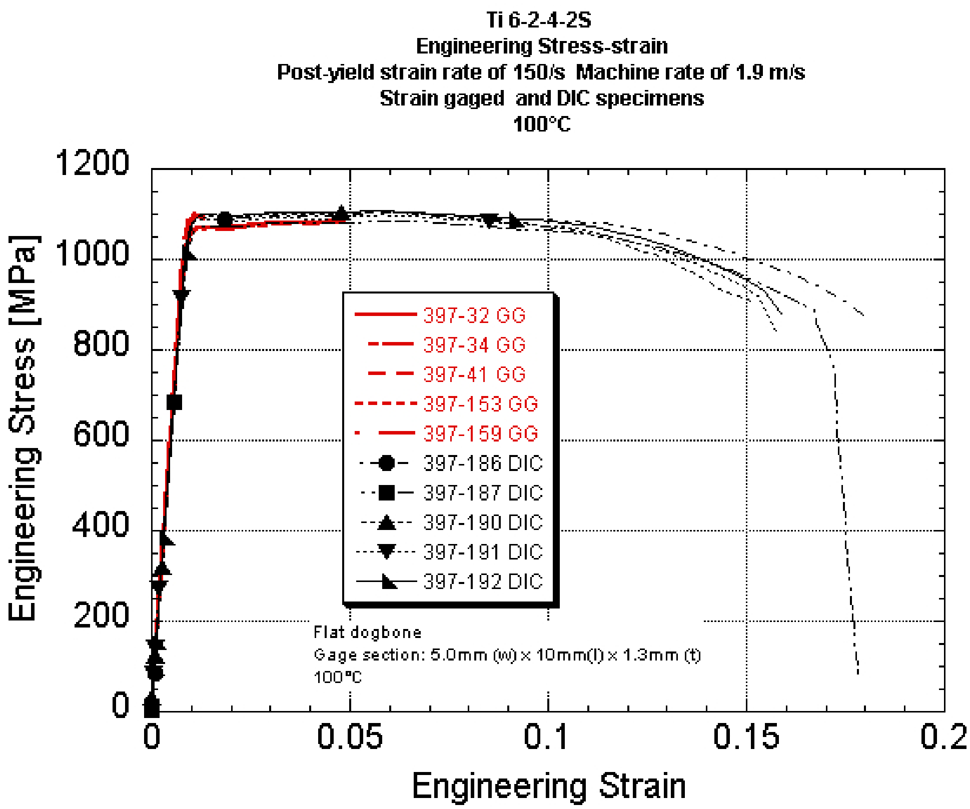


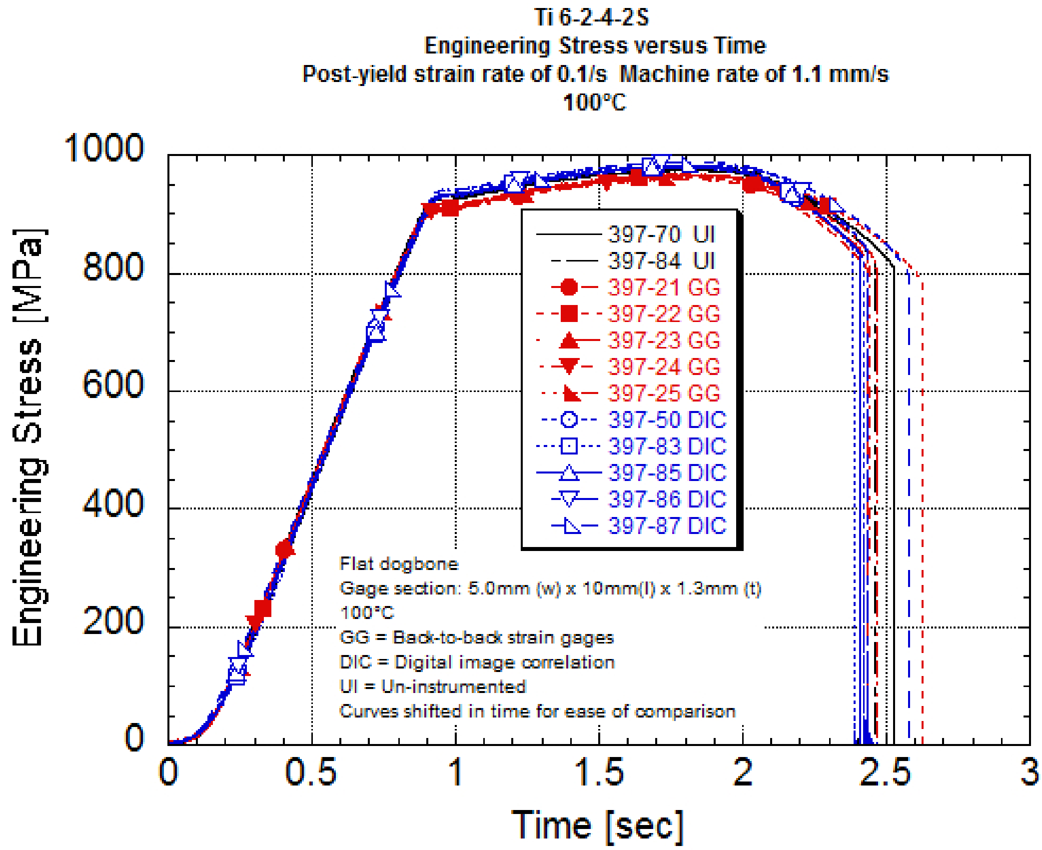
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 12/s Machine rate of 125 mm/s
Strain gaged and DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
1200
0
0.05
0.1
0.15
0.2
397-26 GG
397-27 GG
397-28 GG
397-29 GG
397-30 GG
397-33 GG
397-93 DIC
397-94 DIC
397-95 DIC
397-96 DIC
397-97 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

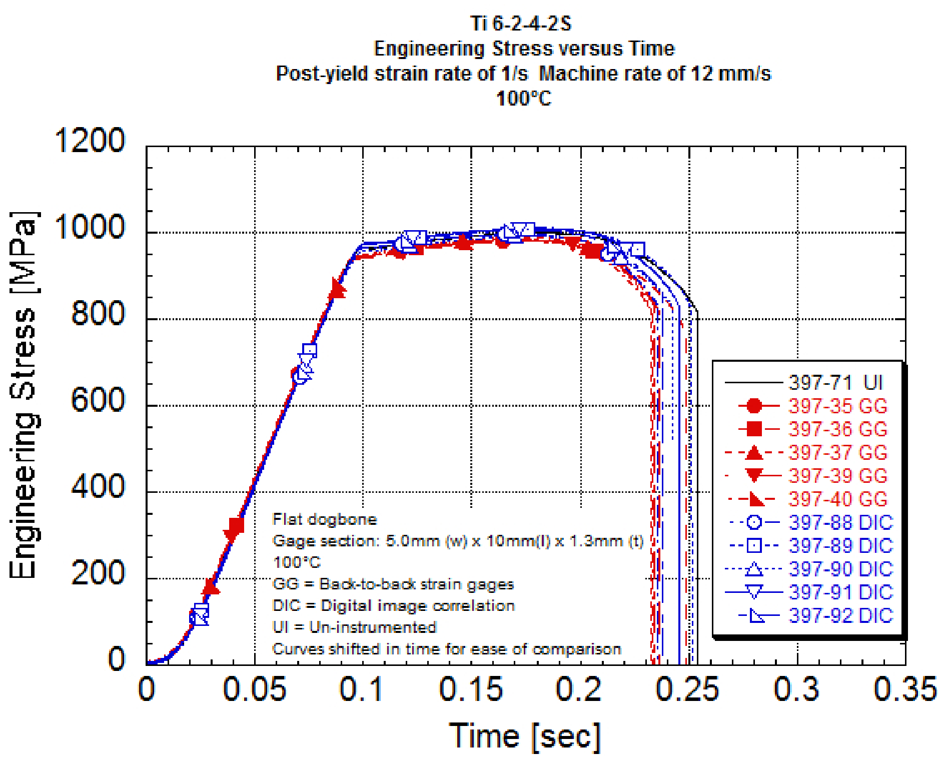


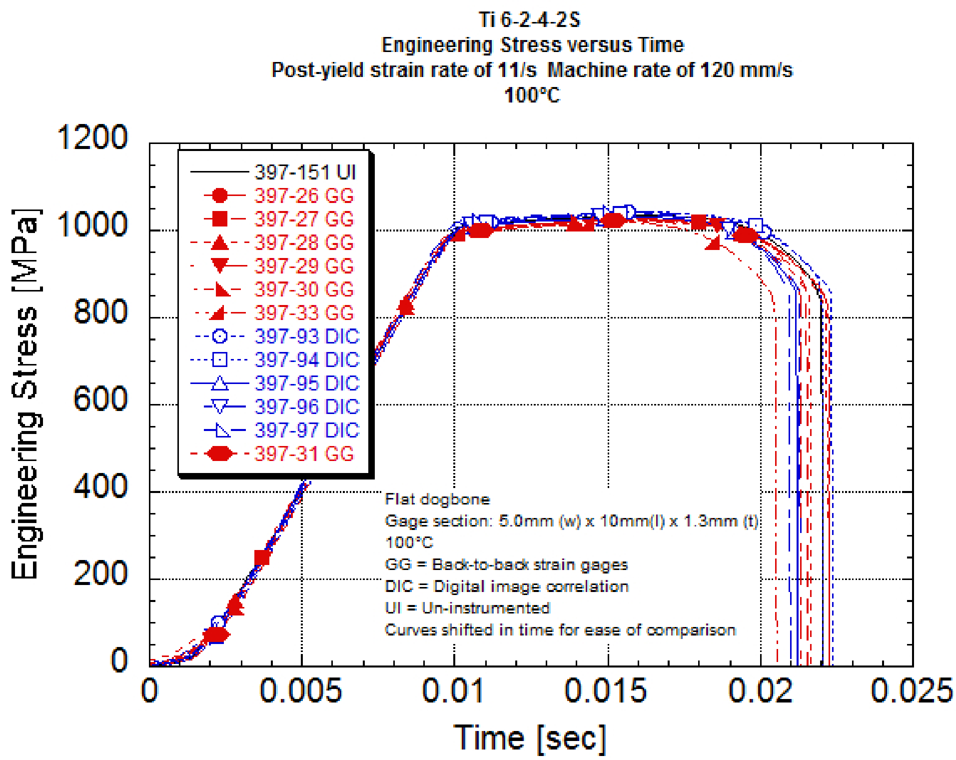
Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 150/s Machine rate of 1.9 m/s
DIC specimens
100°C
Engineering Stress [MPa]
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
Engineering Strain
397-186
397-187
397-190
397-191
397-192
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C

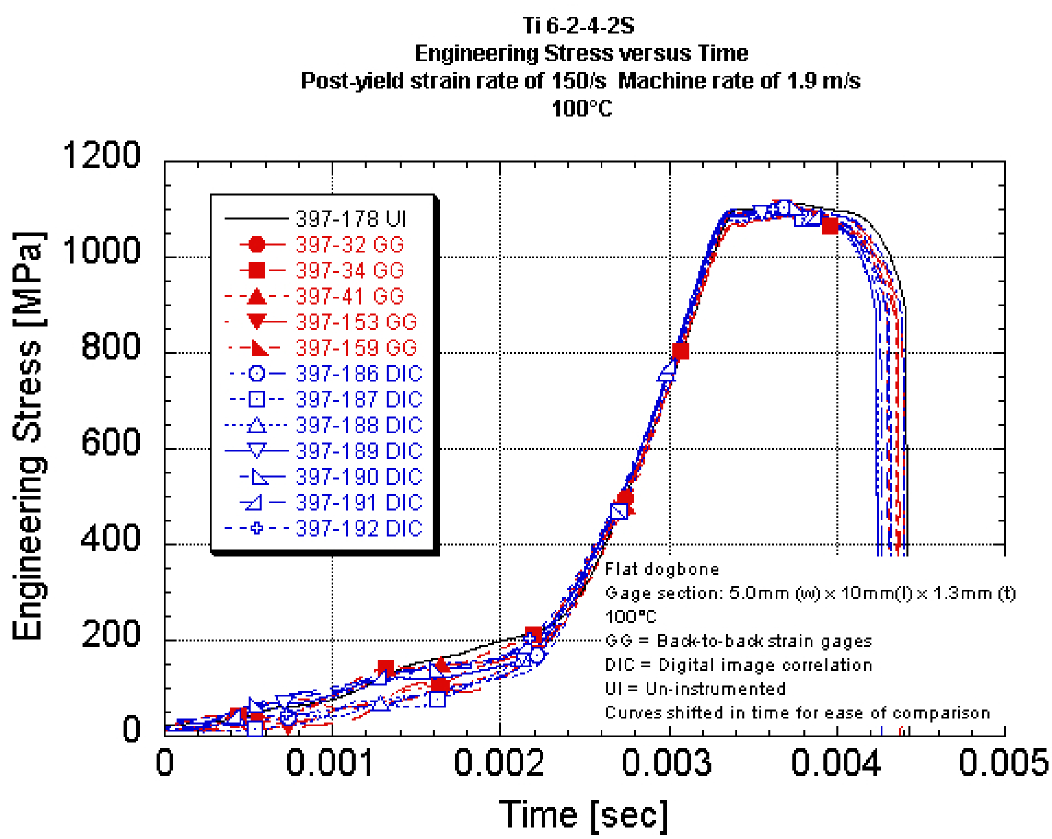

Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 100/s Machine rate of 1.8 m/s
Strain gaged specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-32
397-34
397-41
397-153 WK gages
397-159 WK gages
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
200°C


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 150/s Machine rate of 1.9 m/s
Strain gaged and DIC specimens
100°C
Engineering Stress [MPa]
Engineering Strain
397-32 GG
397-34 GG
397-41 GG
397-153 GG
397-159 GG
397-186 DIC
397-187 DIC
397-190 DIC
397-191 DIC
397-192 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 0.1/s Machine rate of 1.1 mm/s
100°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
0
0.5
1
1.5
2
2.5
3
397-70 UI
397-84 UI
397-21 GG
397-22 GG
397-23 GG
397-24 GG
397-25 GG
397-50 DIC
397-83 DIC
397-85 DIC
397-86 DIC
397-87 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 1/s Machine rate of 12 mm/s
100°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
1200
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
397-71 UI
397-35 GG
397-36 GG
397-37 GG
397-39 GG
397-40 GG
397-88 DIC
397-89 DIC
397-90 DIC
397-91 DIC
397-92 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 11/s Machine rate of 120 mm/s
100°C
Engineering Stress [MPa]
Time [sec]
397-151 UI
397-26 GG
397-27 GG
397-28 GG
397-29 GG
397-30 GG
397-33 GG
397-93 DIC
397-94 DIC
397-95 DIC
397-96 DIC
397-97 DIC
397-31 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 150/s Machine rate of 1.9 m/s
100°C
Engineering Stress [MPa]
Time [sec]
397-178 UI
397-32 GG
397-34 GG
397-41 GG
397-153 GG
397-159 GG
397-186 DIC
397-187 DIC
397-188 DIC
397-189 DIC
397-190 DIC
397-191 DIC
397-192 DIC
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
100°C
GG = Back-to-back strain gages
DIC = Digital image correlation
UI = Un-instrumented
Curves shifted in time for ease of comparison

APPENDIX G: MECH PROPS & SUMMARY GRAPHS – 200°C

Table G1. Mechanical Properties of Ti 6-2-4-2S at 200°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness

Strain measured with gages (WK-06-062AP-350)

	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]
200°C Un-instrumented 0.1/s	3/7/16	397-80	876	-	-	717	-	1.12	0.112	-	-	-
200°C Un-instrumented 1/s	3/7/16	397-81	915	-	-	756	-	11.3	1.13	-	-	-
200° Gaged & Un-instrumented 10/s	5/12/16	397-72	946	900	0.950	774	120	125	12.5	10.5	10.3	1.23-1.29
	5/11/16	397-73	948	906	0.964	784	119	124	12.4	9.64	9.53	1.2-1.26
	5/12/16	397-74	934	887	0.948	760	119	125	12.5	9.29	9.18	1.14-1.19
	5/12/16	397-75	948	904	0.968	777	118	125	12.5	10.0	9.88	1.15-1.21
	5/11/16	397-152	953	903	0.965	768	118	124	12.4	8.12		1.18-1.32
	5/12/16	397-158	939	893	0.985	763	119	125	12.5	8.30		1.02-1.18
	3/7/16	397-82	944	-	-	768	-	127	12.7	-	-	-
	5/16/16	397-98	975	-	-	793	-	126	12.6	-	-	-
Average			***948***	***898***	***0.963***	***773***	***119***					
Std.Dev.			***12.3***	***7.46***	***0.013***	***11.1***	***0.81***					
Coeff. of Var. [%]			***1.30***	***0.83***	***1.4***	***1.44***	***0.68***					

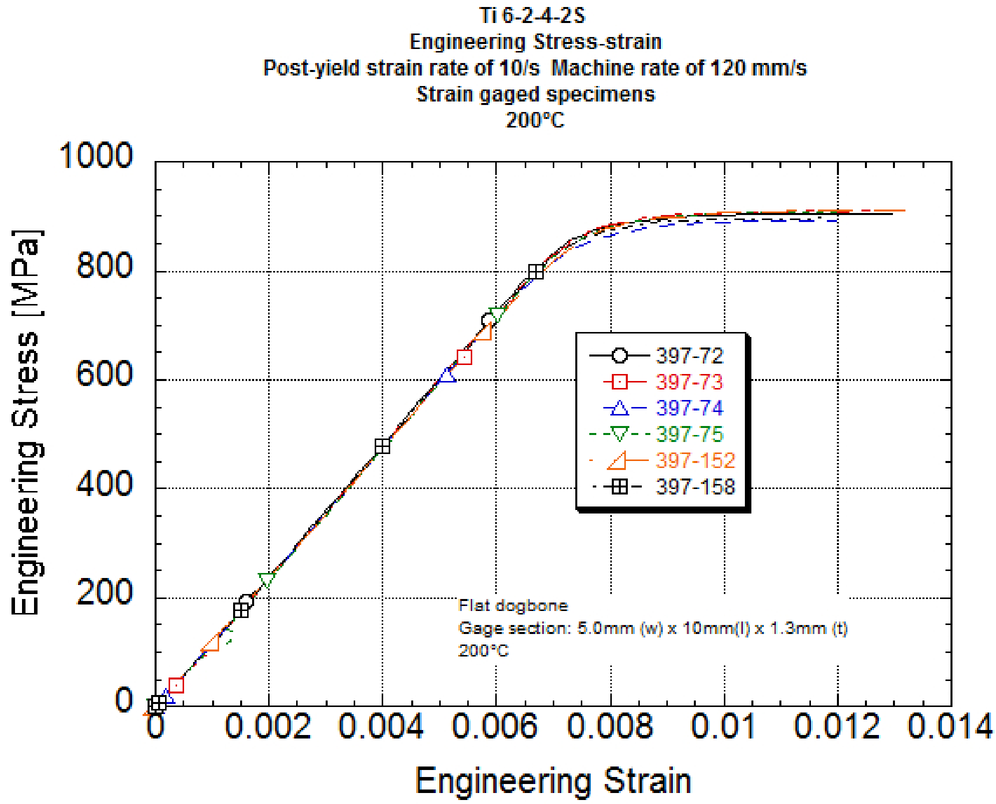
Modulus measured between 0 and 600 MPa

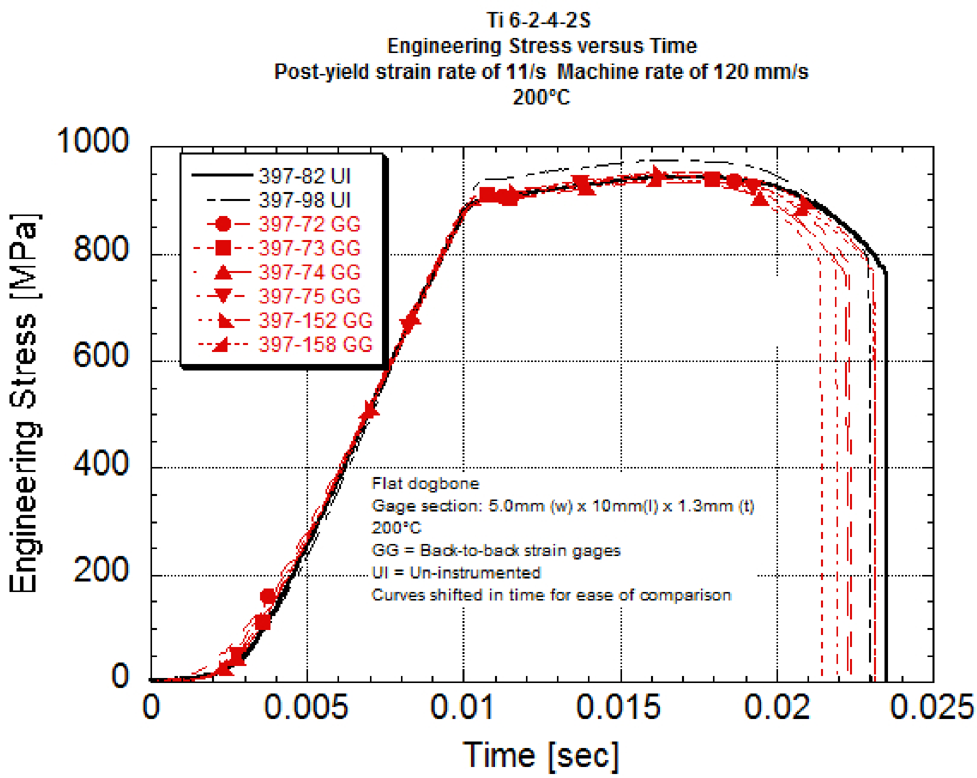
* Strain rate measured over a range before fully developed plastic flow.

Table G2. Reduction in Area Measurements of Ti 6-2-4-2S at 200°C

Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Reduction in Area [%]
0.1	397-80	16.8	39.1
1	397-81	17.5	35.0
12	397-72	-	35.2
	397-73	-	32.8
	397-74	-	44.3
	397-75	-	27.5
	397-82	22.9	33.6
	397-98	-	31.0
	397-152	-	38.7
	397-158	-	35.4
	Average		***34.8***
	Standard Deviation		***5.1***
	Coeff of Variation [%]		***14.6***

Note 1 Average measured strain rate.


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 10/s Machine rate of 120 mm/s
Strain gaged specimens
200°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
397-72
397-73
397-74
397-75
397-152
397-158
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
200°C


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 11/s Machine rate of 120 mm/s
200°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
0
0.005
0.01
0.015
0.02
0.025
397-82 UI
397-98 UI
397-72 GG
397-73 GG
397-74 GG
397-75 GG
397-152 GG
397-158 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
200°C
GG = Back-to-back strain gages
UI = Un-instrumented
Curves shifted in time for ease of comparison

APPENDIX H: MECH PROPS & SUMMARY GRAPHS – 316°C

Table H1. Mechanical Properties of Ti 6-2-4-2S at 316°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with gages (WK-06-062AP-350)

	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering 0.2% Offset Yield Stress [MPa]	Engineering 0.2% Offset Yield Strain [%]	Engineering Failure Stress [Break] [MPa]	Modulus [GPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Measured* Egr Strain Rate [1/s]	Measured* True Strain Rate [1/s]	Strain Range for Strain Rate Calc [%]	Comments
316°C Uninstrumented 0.1/s	7/12/16	397-193	834	-	-	711	-	1.12	0.112	-	-	-	
	7/19/16	397-194	827	-	-	692	-	1.12	0.112	-	-	-	
	7/19/16	397-195	830	-	-	699	-	1.12	0.112	-	-	-	
	7/19/16	397-196	832	-	-	705	-	1.11	0.111	-	-	-	
	7/19/16	397-197	842	-	-	711	-	1.11	0.111	-	-	-	
Average			***833***			***704***							
Std.Dev.			***5.8***			***8.0***							
Coeff. of Var. [%]			***0.69***			***1.14***							
316°C Uninstrumented 1/s	7/21/16	397-198	852	-	-	702	-	11.2	1.12	-	-	-	
	7/21/16	397-199	851	-	-	699	-	11.2	1.12	-	-	-	
	7/25/16	397-200	853	-	-	703	-	11.2	1.12	-	-	-	
	7/26/16	397-201	828	-	-	681	-	11.2	1.12	-	-	-	
	7/26/16	397-202	841	-	-	672	-	11.2	1.12	-	-	-	
Average			***845***			***691***							
Std.Dev.			***10.5***			***14.0***							
Coeff. of Var. [%]			***1.24***			***2.02***							
316°C Gaged and Un-instrumented 10/s	5/16/16	397-76	855	787	0.850	661	121	125	12.5	13.1	12.9	1.22-1.44	Single gage modulus
	5/16/16	397-78	854	785	0.875	675	116	125	12.5	9.46	9.36	1.0-1.12	
	6/16/16	397-154	862	794	0.866	691	119	121	12.1	7.04	6.98	0.86-0.94	
	7/7/16	397-155	857	789	0.873	665	117	121	12.1	7.80	7.72	1.0-1.08	
	7/7/16	397-156	857	775	0.863	643	117	122	12.2	5.17	5.12	0.9-0.97	
	7/12/16	397-157	868	800	0.826	686	128	122	12.2	8.91	8.82	0.98-1.03	
	5/25/16	397-117	854	-	-	700	-	126	12.6	-	-	-	Flame spray strain gage
	7/26/16	397-203	868	-	-		-	121	12.1	-	-	-	
	5/16/16	397-49	875	-	-	698	-	125	12.5	-	-	-	
Average			***861***	***788***	***0.859***	***677***	***120***						
Std.Dev.			***7.7***	***8.59***	***0.02***	***20.1***	***4.24***						
Coeff. of Var. [%]			***0.89***	***1.09***	***2.1***	***2.97***	***3.54***						

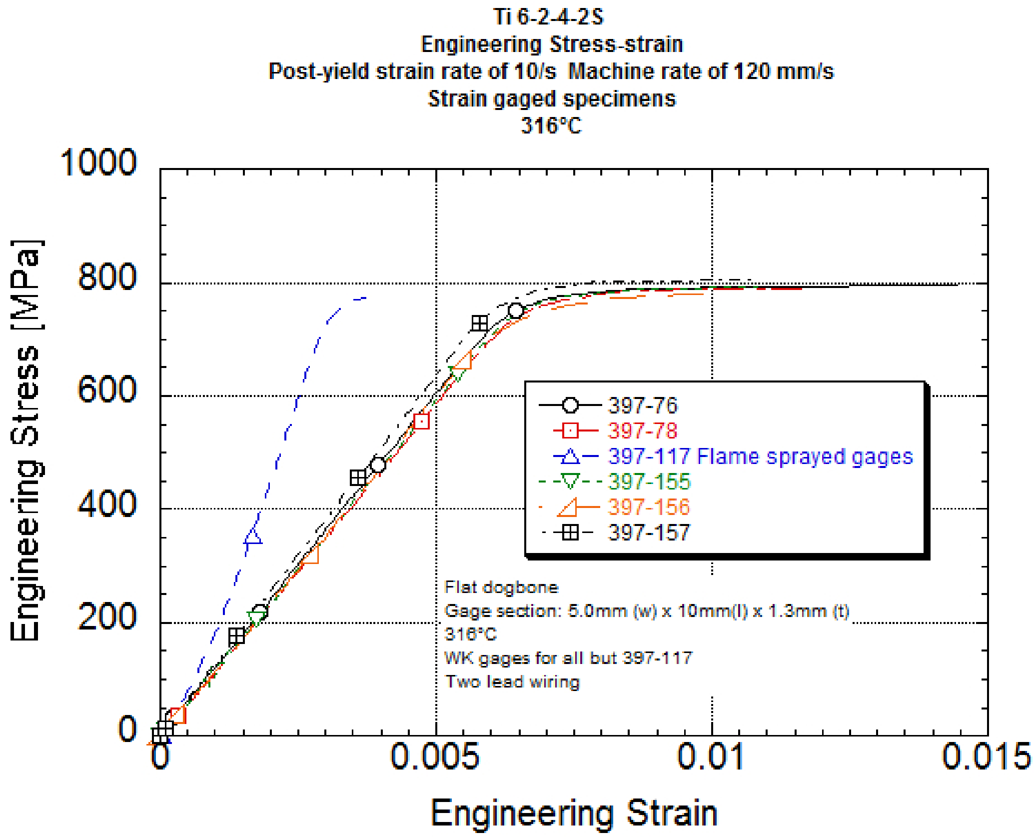
Modulus measured between 0 and 600 MPa

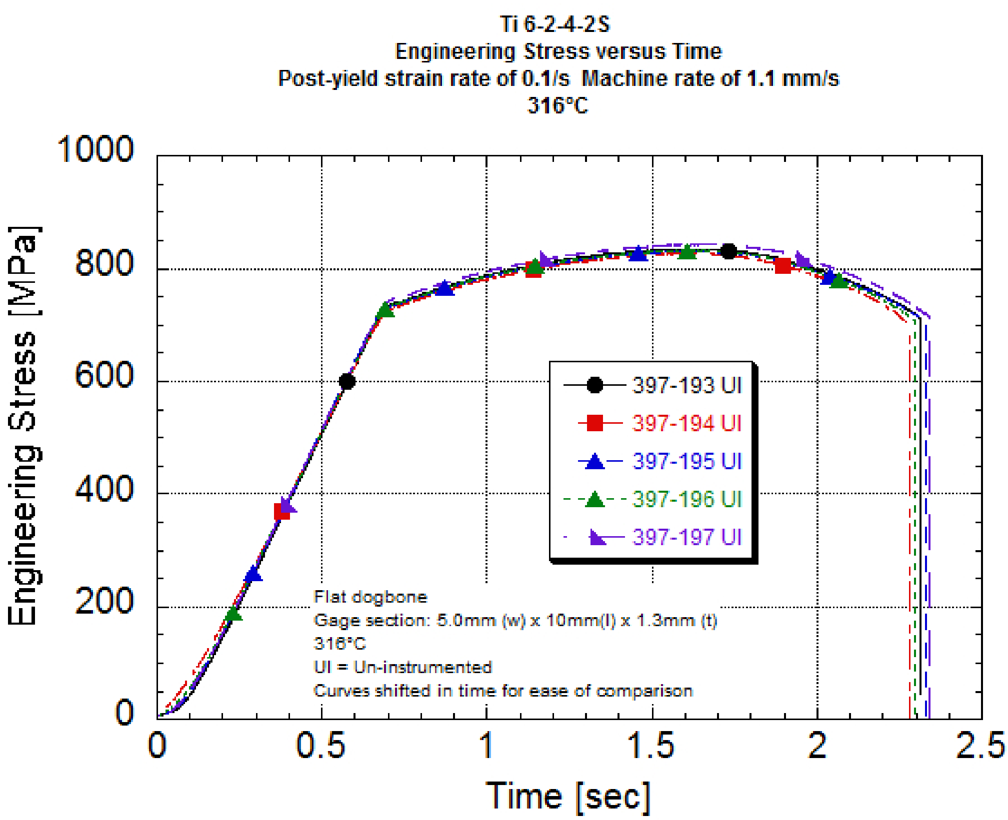
* Strain rate measured over a range before fully developed plastic flow.

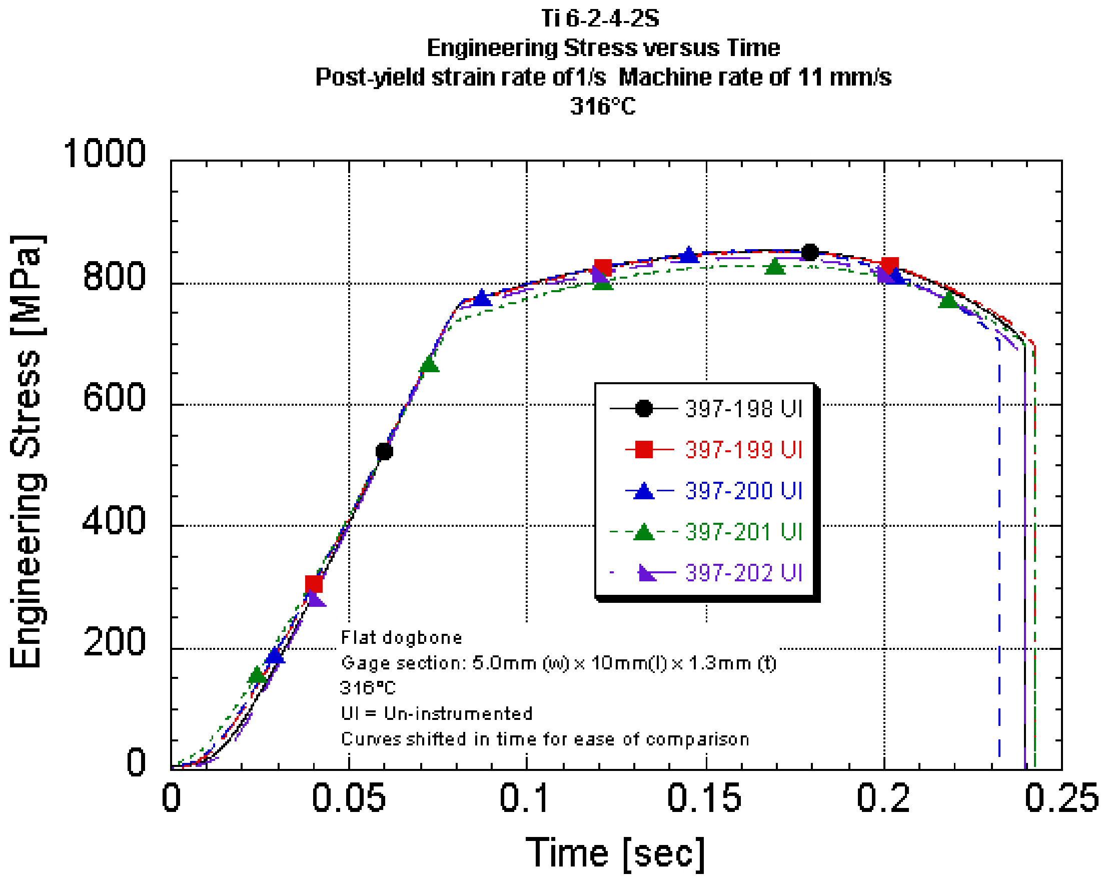
Table H2. Reduction in Area Measurements of Ti 6-2-4-2S at 316°C

Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Reduction in Area [%]
0.1	397-193	21.1	34.0
	397-194	18.4	36.3
	397-195	21.9	38.3
	397-196	20.3	34.2
	397-197	20.8	40.6
	Average	***20.5***	***36.7***
	Standard Deviation	***1.3***	***2.8***
	Coeff of Variation [%]	***6.4***	***7.6***
1	397-198	19.4	34.1
	397-199	25.2	39.2
	397-200	15.6	40.2
	397-201	24.4	38.3
	397-202	19.5	35.2
	Average	***20.8***	***37.4***
	Standard Deviation	***4.0***	***2.6***
	Coeff of Variation [%]	***19.0***	***7.0***
12	397-49		35.5
	397-76		35.6
	397-78		30.6
	397-117		38.1
	397-154		35.6
	397-155		42.2
	397-156		34.8
	397-157		31.9
	397-203	34.0	39.7
	Average		***36.0***
	Standard Deviation		***3.6***
	Coeff of Variation [%]		***10.1***

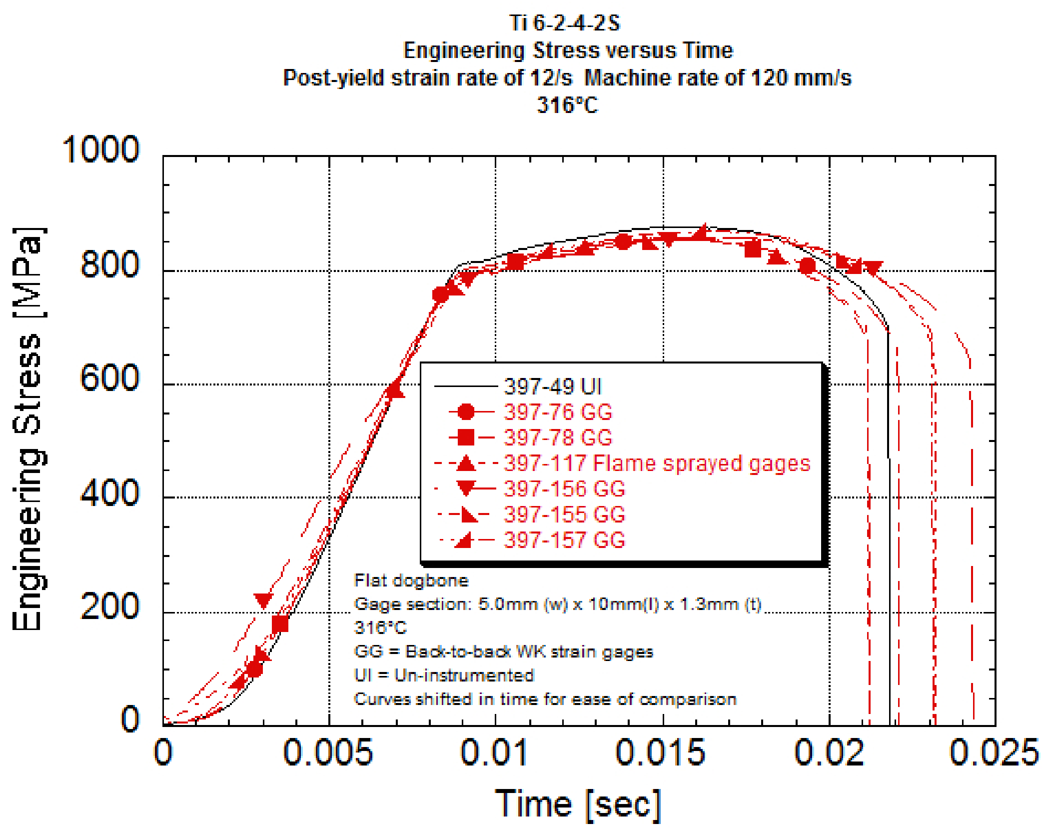
Note 1 Average measured strain rate.


Ti 6-2-4-2S
Engineering Stress-strain
Post-yield strain rate of 10/s Machine rate of 120 mm/s
Strain gaged specimens
316°C
Engineering Stress [MPa]
Engineering Strain
0
200
400
600
800
1000
0
0.005
0.01
0.015
397-76
397-78
397-117 Flame sprayed gages
397-155
397-156
397-157
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
316°C
WK gages for all but 397-117
Two lead wiring


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 0.1/s Machine rate of 1.1 mm/s
316°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
0
0.5
1
1.5
2
2.5
397-193 UI
397-194 UI
397-195 UI
397-196 UI
397-197 UI
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
316°C
UI = Un-instrumented
Curves shifted in time for ease of comparison



Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of1/s Machine rate of 11 mm/s
316°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
0
0.05
0.1
0.15
0.2
0.25
397-198 UI
397-199 UI
397-200 UI
397-201 UI
397-202 UI
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
316°C
UI = Un-instrumented
Curves shifted in time for ease of comparison



Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 12/s Machine rate of 120 mm/s
316°C
Engineering Stress [MPa]
Time [sec]
0
200
400
600
800
1000
0
0.005
0.01
0.015
0.02
0.025
397-49 UI
397-76 GG
397-78 GG
397-117 Flame sprayed gages
397-156 GG
397-155 GG
397-157 GG
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
316°C
GG = Back-to-back WK strain gages
UI = Un-instrumented
Curves shifted in time for ease of comparison

APPENDIX I: MECH PROPS & SUMMARY GRAPHS – 427°C

Table I1. Mechanical Properties of Ti 6-2-4-2S at 427°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with HFP-12-125-SPW gages applied using flame spray

427°C	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering Failure Stress [Break] [MPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Comments
Un-instrumented 0.1/s	5/27/16	397-168	769	665	1.12	0.112	
	7/28/16	397-204	773	676	1.10	0.110	
	7/29/16	397-205	775	666	1.13	0.113	
	7/29/16	397-206	776	663	1.13	0.113	
	7/29/16	397-207	756	666	1.11	0.111	
Average			***770***	***667***			
Std.Dev.			***8.0***	***5.2***			
Coeff. of Var. [%]			***1.03***	***0.78***			
Un-instrumented 1/s	5/26/16	397-165	757	641	11.2	1.12	
	7/27/16	397-209	750	630	11.1	1.11	
	7/28/16	397-210	778	614	11.0	1.10	
	7/28/16	397-211	775	651	11.0	1.10	
	7/28/16	397-212	779	654	11.0	1.101	
Average			***768***	***638***			
Std.Dev.			***13.4***	***16.6***			
Coeff. of Var. [%]			***1.75***	***2.60***			
Gaged and Un-instrumented 10/s	6/6/16	397-105	791	638	124	12.4	Note 1
	5/24/16	397-126	779	623	125	12.5	Note 1
	5/26/16	397-164	761	613	126	12.6	
	7/26/16	397-214	793	613	122	12.2	
	7/27/16	397-215	791	621	123	12.3	
	7/27/16	397-216	803	641	122	12.2	
	7/27/16	397-217	799	604	124	12.4	
Average			***788***	***622***			
Std.Dev.			***14.2***	***13.6***			
Coeff. of Var. [%]			***1.81***	***2.18***			

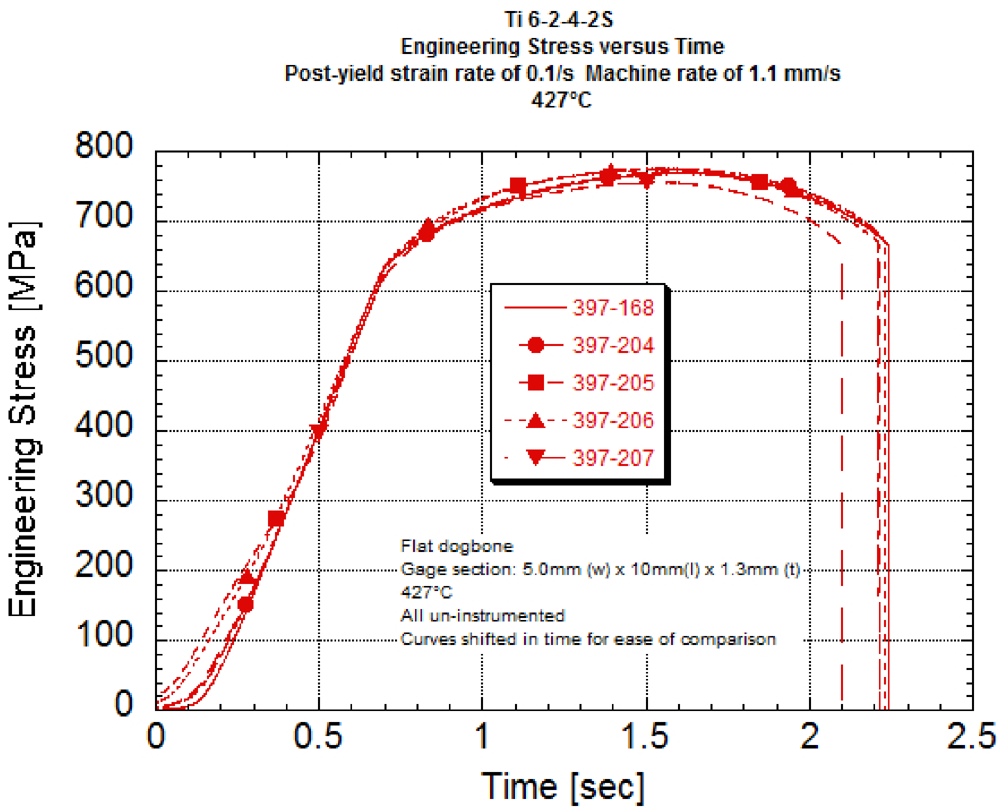
Note 1 Flame sprayed applied gages using Hiteco HFP-12-125-SPW gages. Strain data not valid.

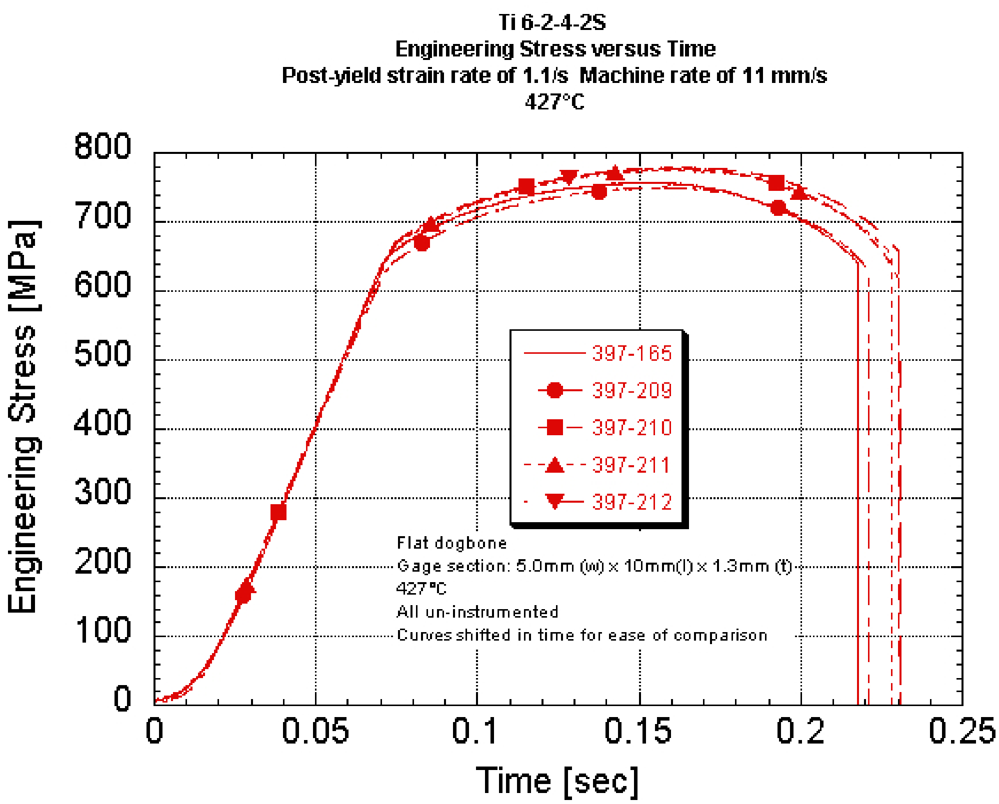
Table I2. Reduction in Area Measurements of Ti 6-2-4-2S at 427°C

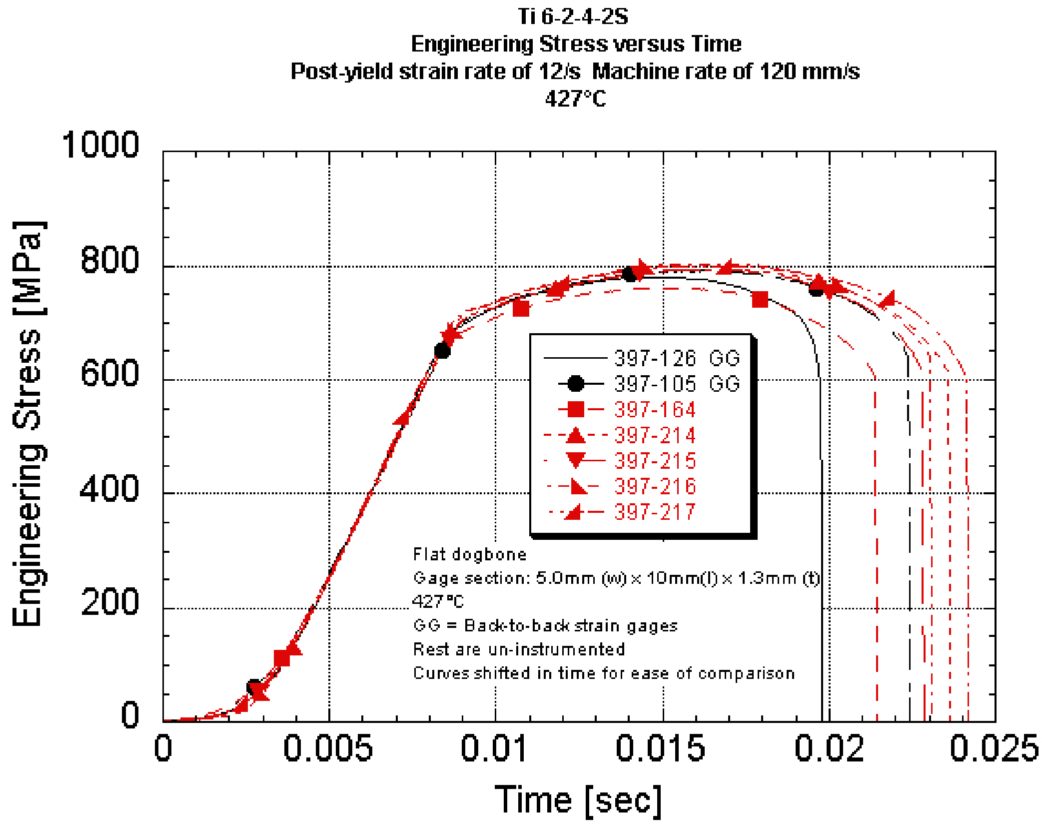
Post-Yield Engineering Strain Rate(1) [1/s]	UDRI Specimen ID	Gage Elongation [%]	Reduction in Area [%]
0.1	397-168	-	34.4
	397-204	21.0	33.7
	397-205	25.9	42.1
	397-206	22.5	30.9
	397-207	22.5	29.5
	Average	***23.0***	***34.1***
	Standard Deviation	***2.1***	***4.9***
	Coeff of Variation [%]	***9.2***	***14.3***
1	397-165	-	35.6
	397-209	9.57*	40.9
	397-210	26.0	43.5
	397-211	23.3	36.3
	397-212	23.2	37.2
	Average	***24.2***	***38.7***
	Standard Deviation	***1.6***	***3.4***
	Coeff of Variation [%]	***6.6***	***8.7***
12	397-214	2.81*	39.7
	397-216	23.9	40.2
	397-215	-	43.4
	397-105	-	36.8
	397-217	20.9	41.9
	397-126	-	32.1
	397-164	-	41.3
	Average	***22.4***	***39.3***
	Standard Deviation	***2.1***	***3.8***
	Coeff of Variation [%]	***9.5***	***9.7***

Note 1 Average strain rate.

*Excluded from average


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 0.1/s Machine rate of 1.1 mm/s
427°C
Engineering Stress [MPa]
Time [sec]
397-168
397-204
397-205
397-206
397-207
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
427°C
All un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 1.1/s Machine rate of 11 mm/s
427°C
Engineering Stress [MPa]
Time [sec]
397-165
397-209
397-210
397-211
397-212
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
427°C
All un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 12/s Machine rate of 120 mm/s
427°C
Engineering Stress [MPa]
Time [sec]
397-126 GG
397-105 GG
397-164
397-214
397-215
397-216
397-217
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
427°C
GG = Back-to-back strain gages
Rest are un-instrumented
Curves shifted in time for ease of comparison

APPENDIX J: MECH PROPS & SUMMARY GRAPHS – 538°C, 600°C, AND 650°C

Table J1. Mechanical Properties of Ti 6-2-4-2S at 538°C, 600°C and 650°C

Specimen size: 5W flat dogbone with a 5mm width and 10.0 mm straight gage length. 1.27mm thickness
Strain measured with HFP-12-125-SPW gages applied using flame spray

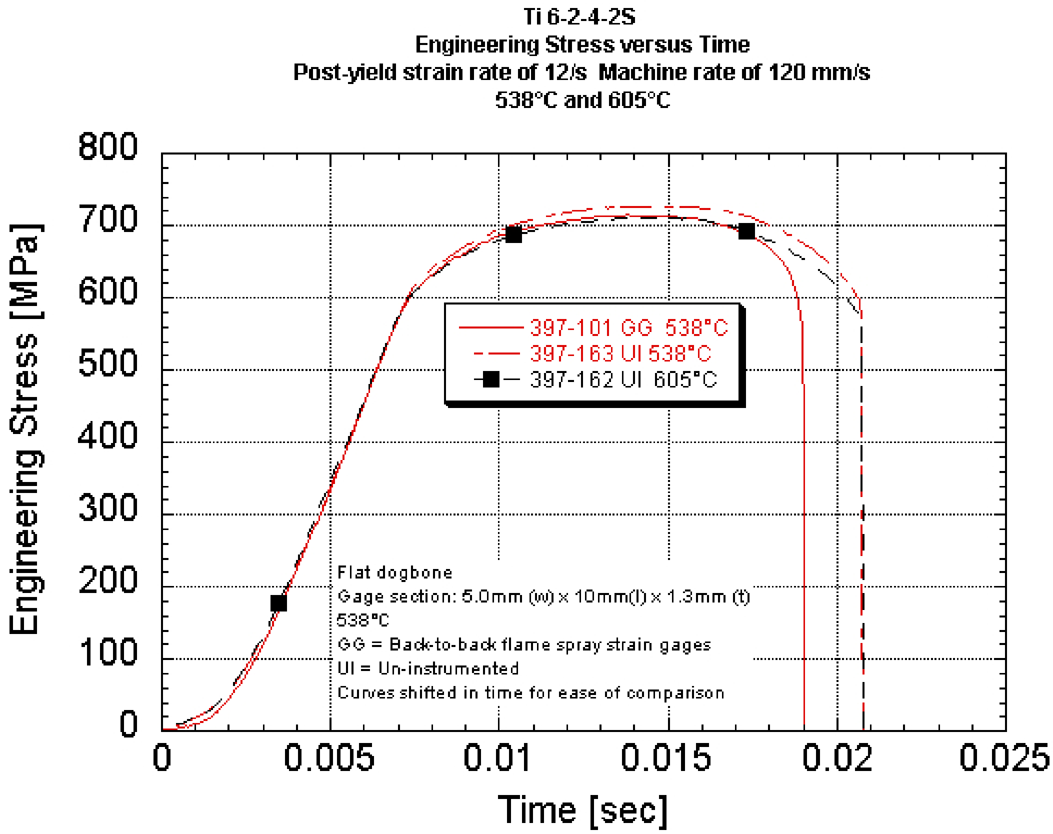
	Test Date	UDRI Specimen ID	Engineering Ultimate Stress [MPa]	Engineering Failure Stress [Break] [MPa]	Machine Rate [mm/s]	Nominal Plastic Strain Rate [1/s]	Comments
538°C Uninstrumented 0.1/s	5/27/16	397-167	729	627	1.12	0.112	
538°C Uninstrumented 1/s	5/27/16	397-166	726	611	11.18	1.118	
538°C Gaged and Uninstrumented 10/s	5/25/16	397-101	714	563	125	12.5	Note 1
	5/26/16	397-163	727	597	125	12.5	
Average			***721***	***580***			
600° Uninstrumented 10/s	5/24/16	397-162	710	565	119	11.9	
650° Gaged & Un-instrumented 10/s	5/18/16	397-104	673	540	126	12.6	Note 1
	5/19/16	397-106	658	552	126	12.6	Note 1
	5/18/16	397-110	672	529	126	12.6	Note 1
	5/23/16	397-113	680	573	126	12.6	Note 1
	5/19/16	397-118	675	538	126	12.6	Note 1
	5/23/16	397-123	674	576	126	12.6	Note 1
	5/23/16	397-161	686	540	126	12.6	
Average			***674***	***550***			
Std.Dev.			***8.8***	***18.2***			
Coeff. of Var. [%]			***1.30***	***3.32***			

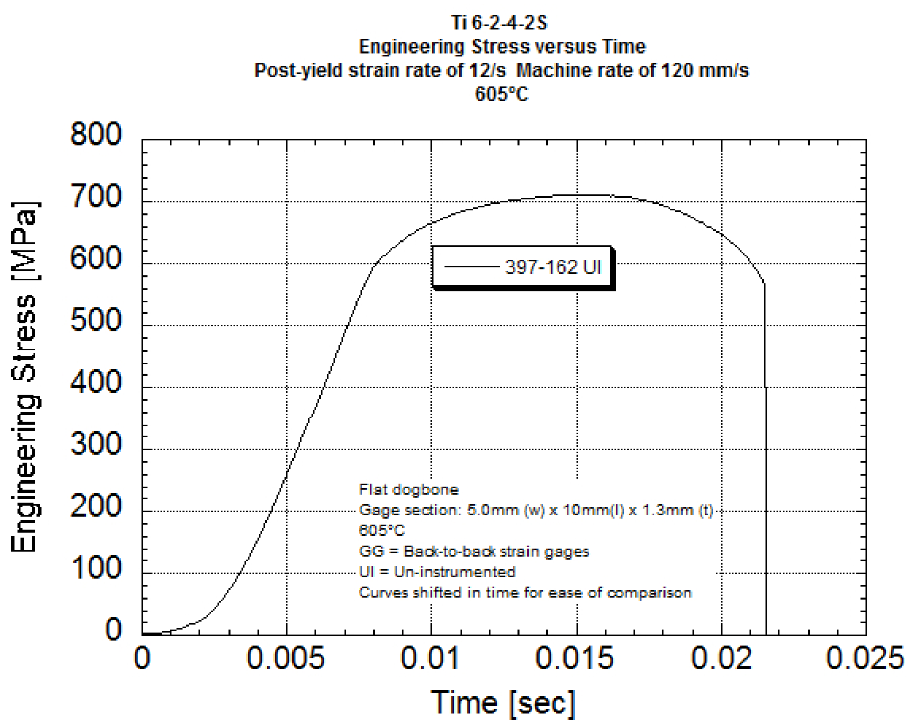
Note 1 Flame sprayed applied gages using Hiteco HFP-12-125-SPW gages. Strain data not valid.

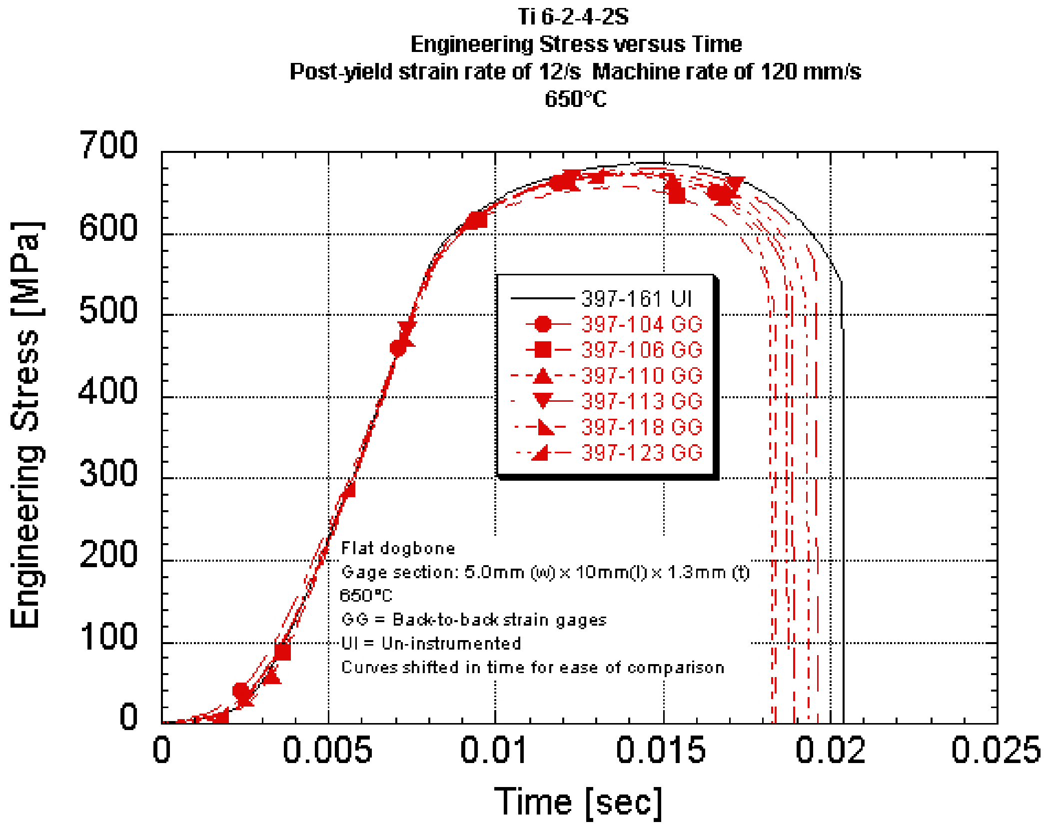
Table J2. Reduction in Area Measurements of Ti 6-2-4-2S at 538°C, 600°C, and 650°C

Test Temperature [°C]	Post-Yield Engineering Strain Rate[(1)] [1/s]	UDRI Specimen ID	Reduction in Area [%]
538	0.1	397-167	45.2
538	1	397-166	45.8
538	12	397-101	34.1
		397-163	34.9
		Average	***34.5***
600	1	397-162	40.3
650	12	397-104	42.9
		397-106	35.3
		397-110	32.3
		397-113	34.4
		397-118	41.6
		397-123	34.7
		397-161	38.0
		Average	***37.0***
		Standard Deviation	***4.0***
		Coeff of Variation [%]	***10.8***

Note 1 Average strain rate.


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 12/s Machine rate of 120 mm/s
538°C and 605°C
Engineering Stress [MPa]
Time [sec]
397-101 GG 538°C
397-163 UI 538°C
397-162 UI 605°C
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
538°C
GG = Back-to-back flame spray strain gages
UI = Un-instrumented
Curves shifted in time for ease of comparison


Ti 6-2-4-2S
Engineering Stress versus Time
Post-yield strain rate of 12/s Machine rate of 120 mm/s
605°C
Engineering Stress [MPa]
Time [sec]
397-162 UI
Flat dogbone
Gage section: 5.0mm (w) x 10mm(l) x 1.3mm (t)
605°C
GG = Back-to-back strain gages
UI = Un-instrumented
Curves shifted in time for ease of comparison



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